Planet Formation in Star-Forming Regions

: from the Solar System to Other Worlds

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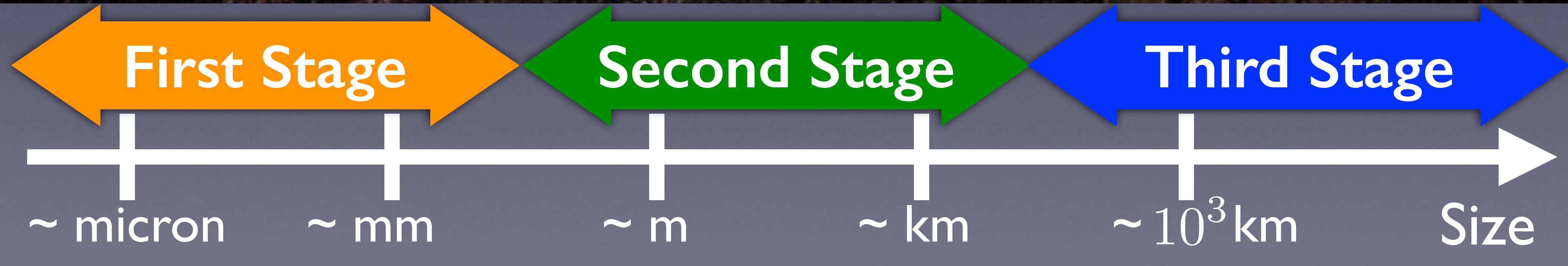
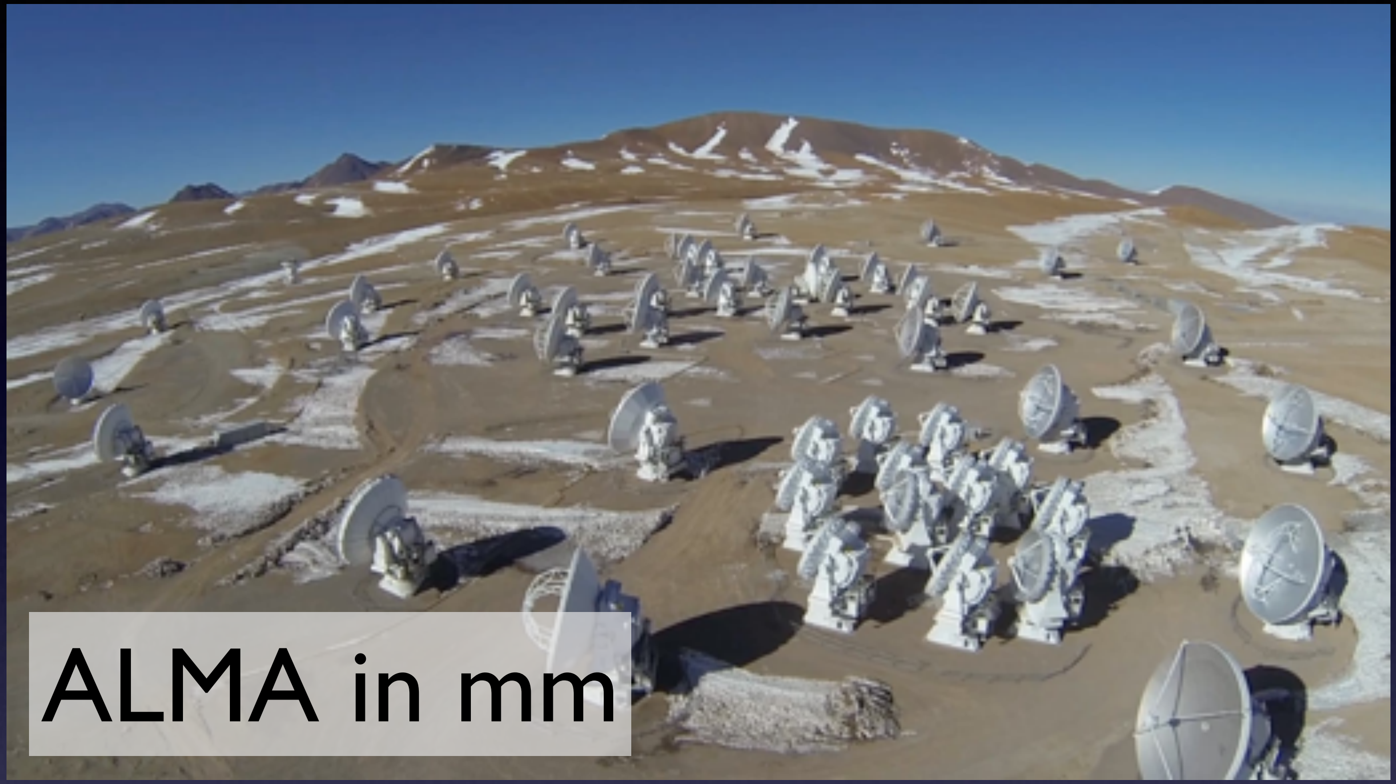
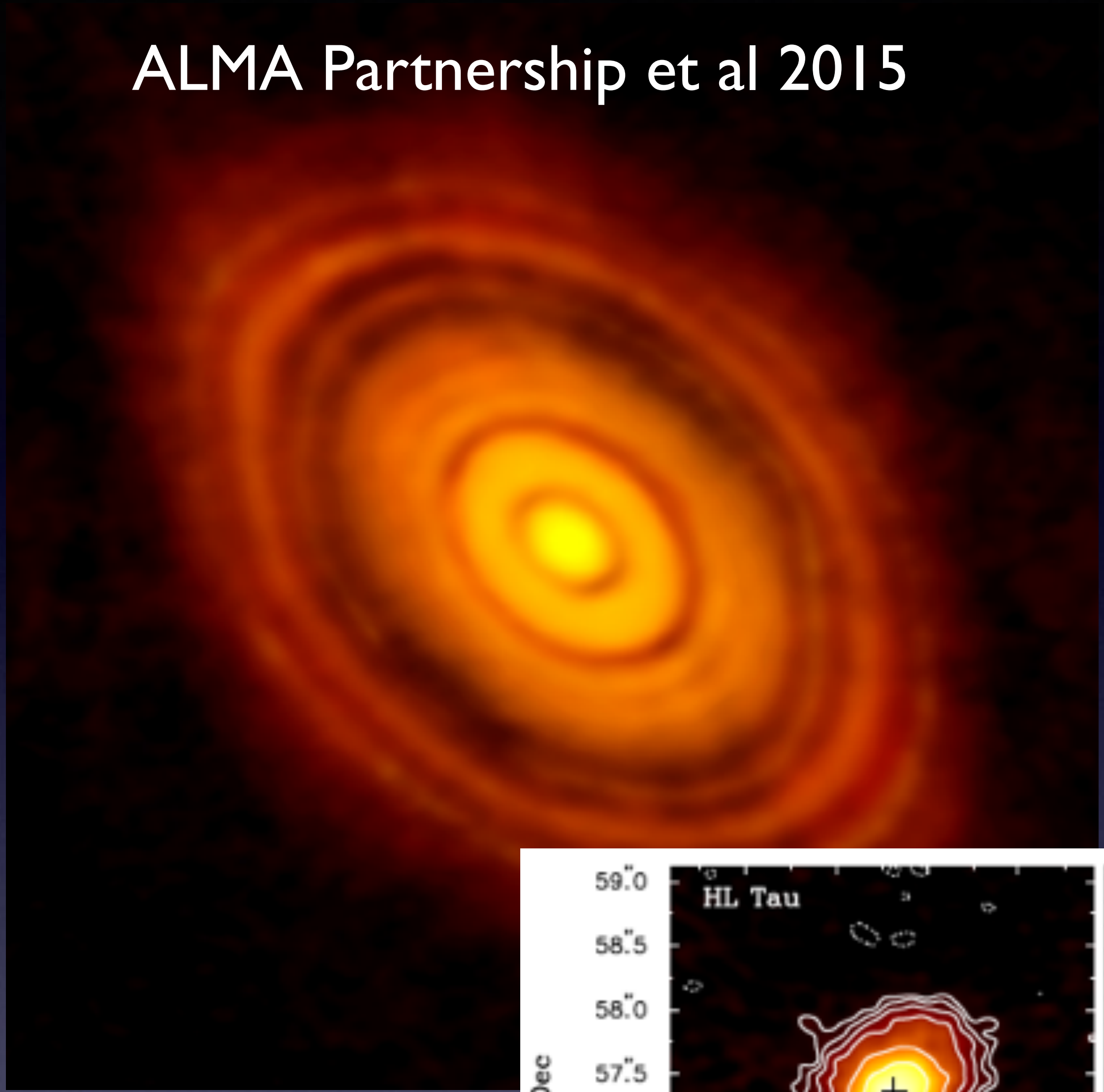
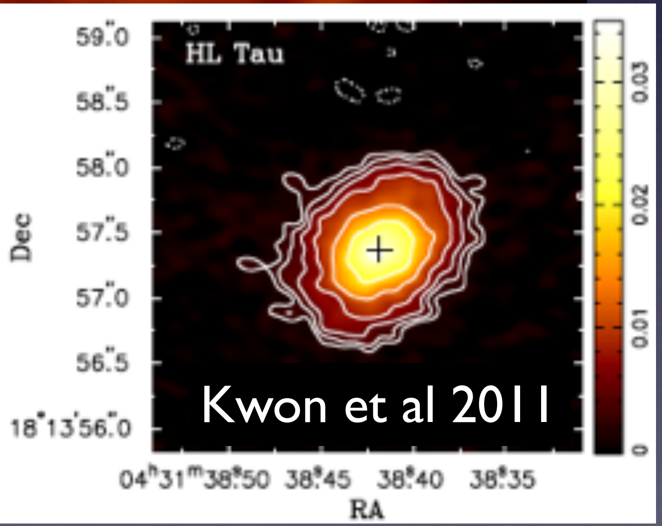


1. Evolution in Astronomical Disk Observations







We can **see** planet-forming regions

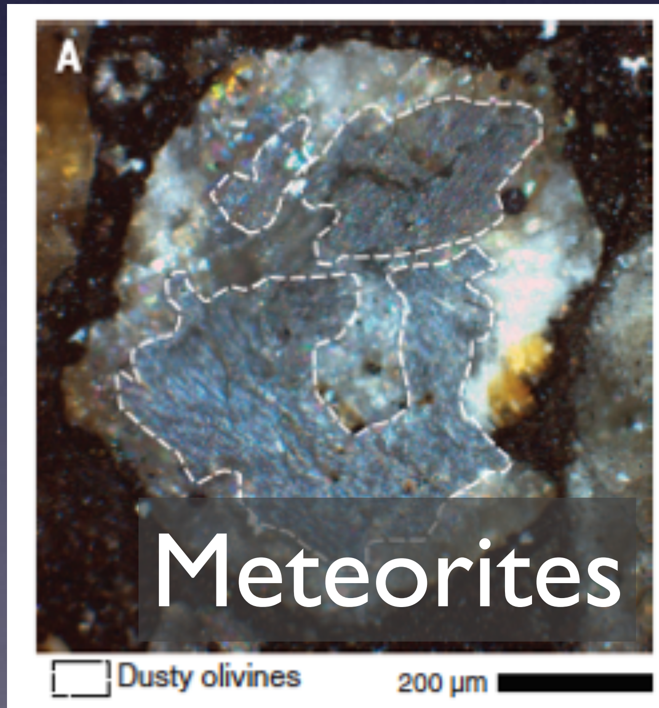
First Stage

JWST is coming soon

~ micron   ~ mm   ~ m   ~ km $\sim 10^3$ km   Size

2. Evolution in Space Engineering & Lab Experiments

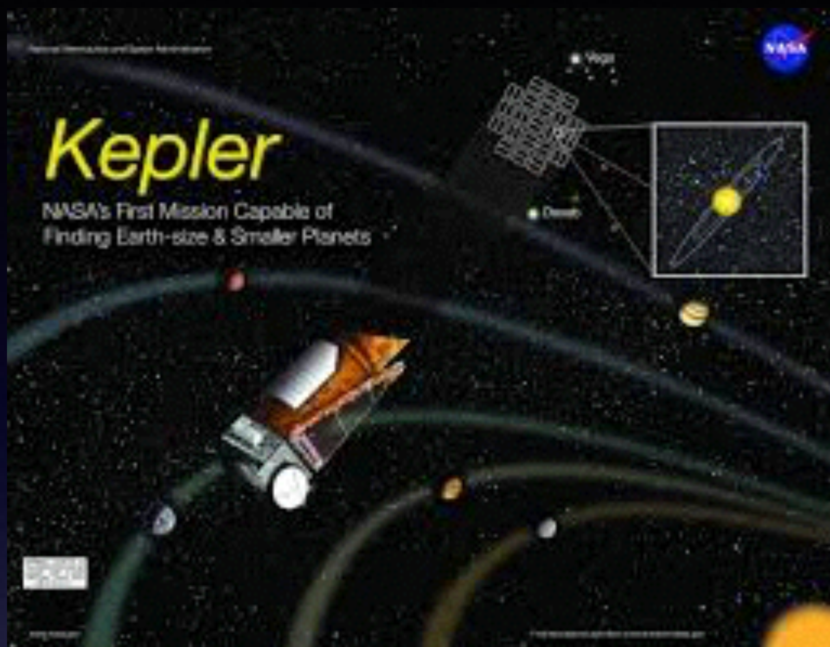
We can **touch** planet-forming materials

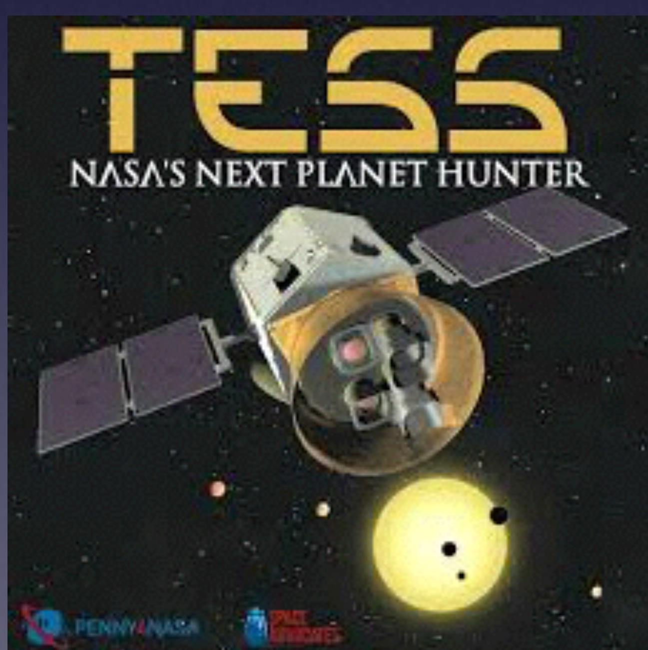


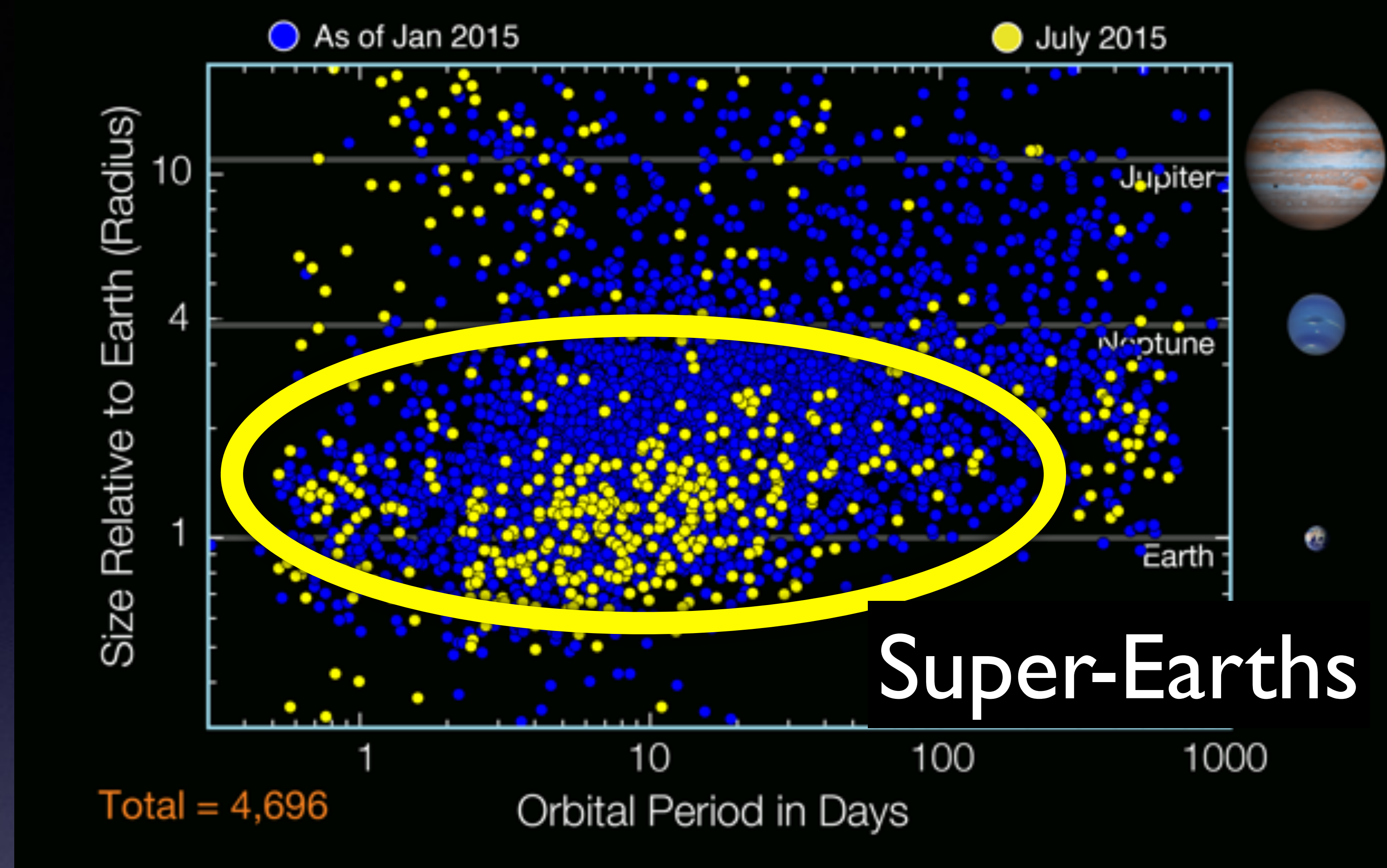
Second Stage

~ micron — ~ mm — ~ m — ~ km — ~ 10^3 km — Size

3. Evolution in the Number of Known (exo)Planets



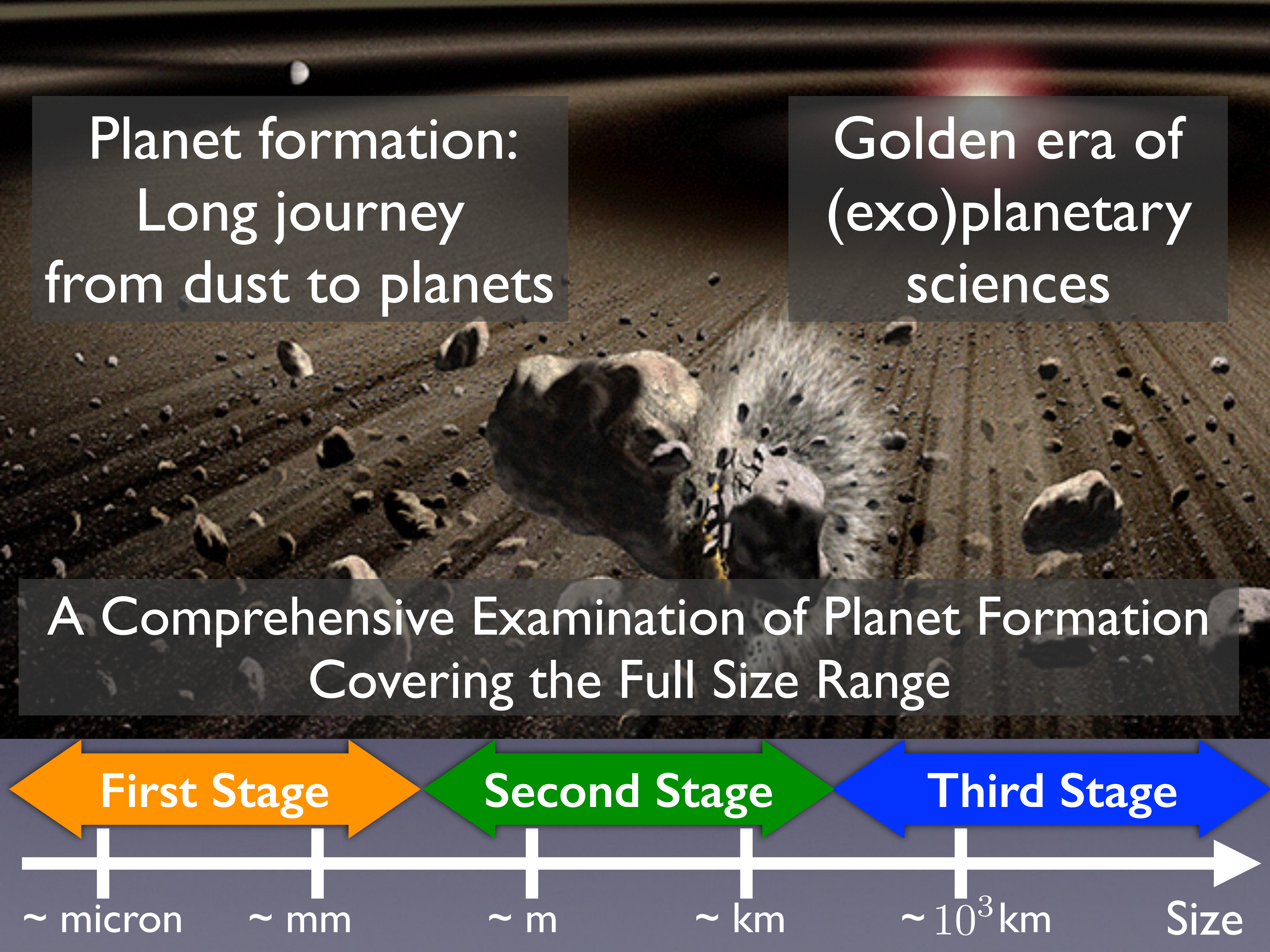




We can **characterize** (exo)planetary systems

Third Stage

~ micron ~ mm ~ m ~ km ~ 10^3 km Size


Planet formation:
Long journey
from dust to planets
Golden era of
(exo)planetary
sciences
A Comprehensive Examination of Planet Formation
Covering the Full Size Range
First Stage
Second Stage
Third Stage
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size

A Comprehensive Examination of Planet Formation

Grain Growth in Star-forming Clouds and Protoplanetary Disks

: **Liu et al 2016**, Harada et al 2017, **Li et al 2017**, Sengupta et al 2017 in prep

Chondrules & Origins of Asteroids

: Hasegawa et al 2016a,b, Wakita et al 2017, Matsumoto et al 2017

Planet Formation and Exoplanet Populations

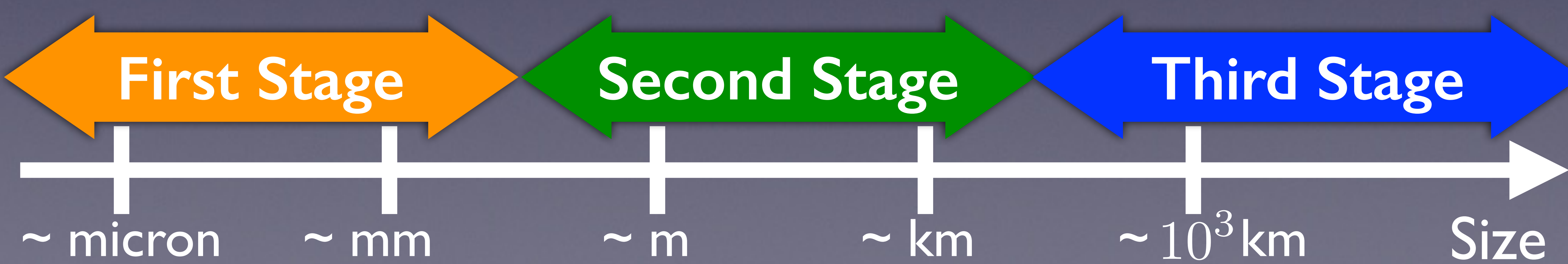
: Hasegawa & Pudritz 2010a,b, 2011a,b, 2012, 2013, Hasegawa & Ida 2013, Hasegawa & Pudritz 2014, Hasegawa & Hirashita 2014, Hasegawa 2016

Protoplanetary Disks

:**Takami et al 2014, Galvan-Madrid et al 2014,** Hasegawa & Takeuchi 2015, **Akiyama et al 2016a,b, Liu et al 2016, Long et al 2017, Liu et al 2017** Hasegawa et al 2017 submitted

Origins of Presolar Grains

: Nozawa et al 2015, Wakita et al 2017



A Comprehensive Examination of Planet Formation

JPL/Caltech, USA: Neal Turner, Joseph Masiero, Mario Flock, Mark Swain, Gautam Vasisht, Pin Chen

Caltech, USA: Konstantin Batygin, Roberta Paladini

Univ of Delaware, USA: Debanjan Sengupta, Sally Dodson-Robinson

McMaster, Canada: Ralph Pudritz

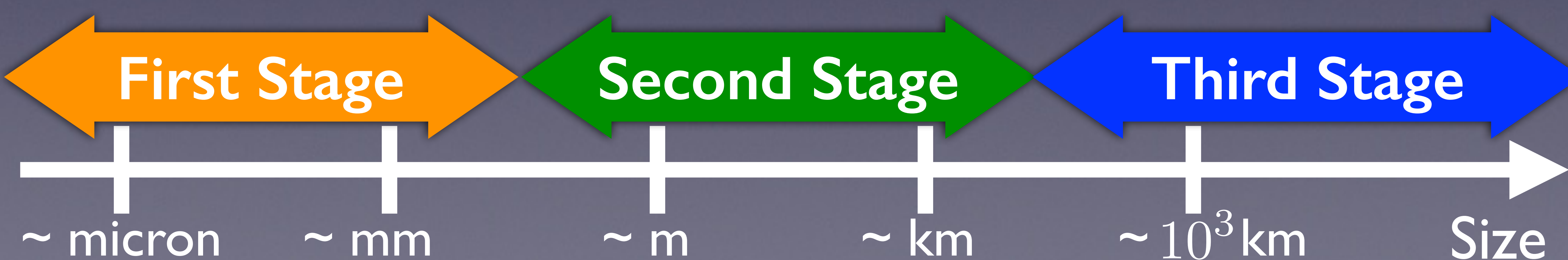
NAOJ, Japan: Eiji Akiyama, Shigeru Wakita, Takaya Nozawa, Yuji Matsumoto, Shouichi Oshino, Jun Hashimoto

TokyoTech, Japan: Satoshi Okuzumi, Shigeru Ida

ASIAA, Taiwan: Naomi Hirano, Hiroyuki, Hirashita, I-Hsiu Li, Pin-Gao Gu, Nanase Harada

ESO, Germany: Hauyu Baobab Liu

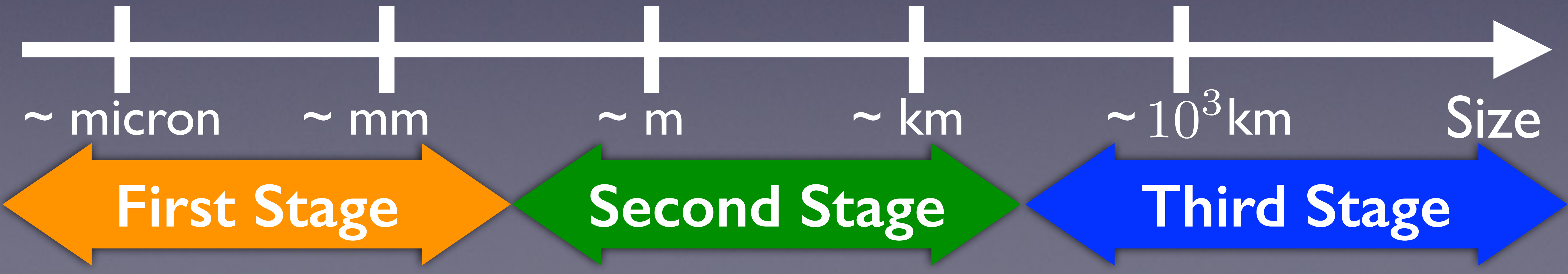
Univ. of Dundee, UK: Soko Matsumura

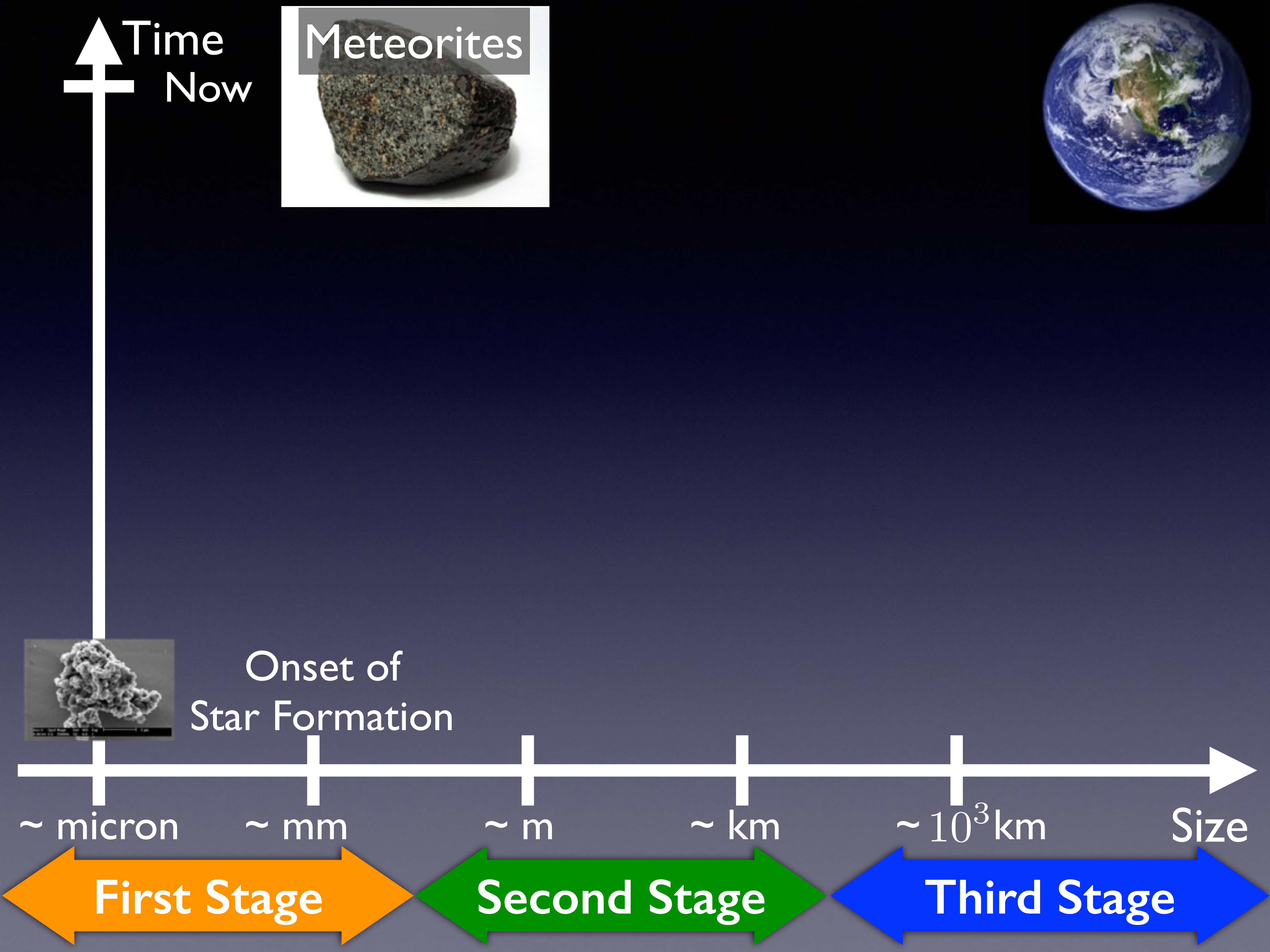


Chondrules: the primitive material in the solar system

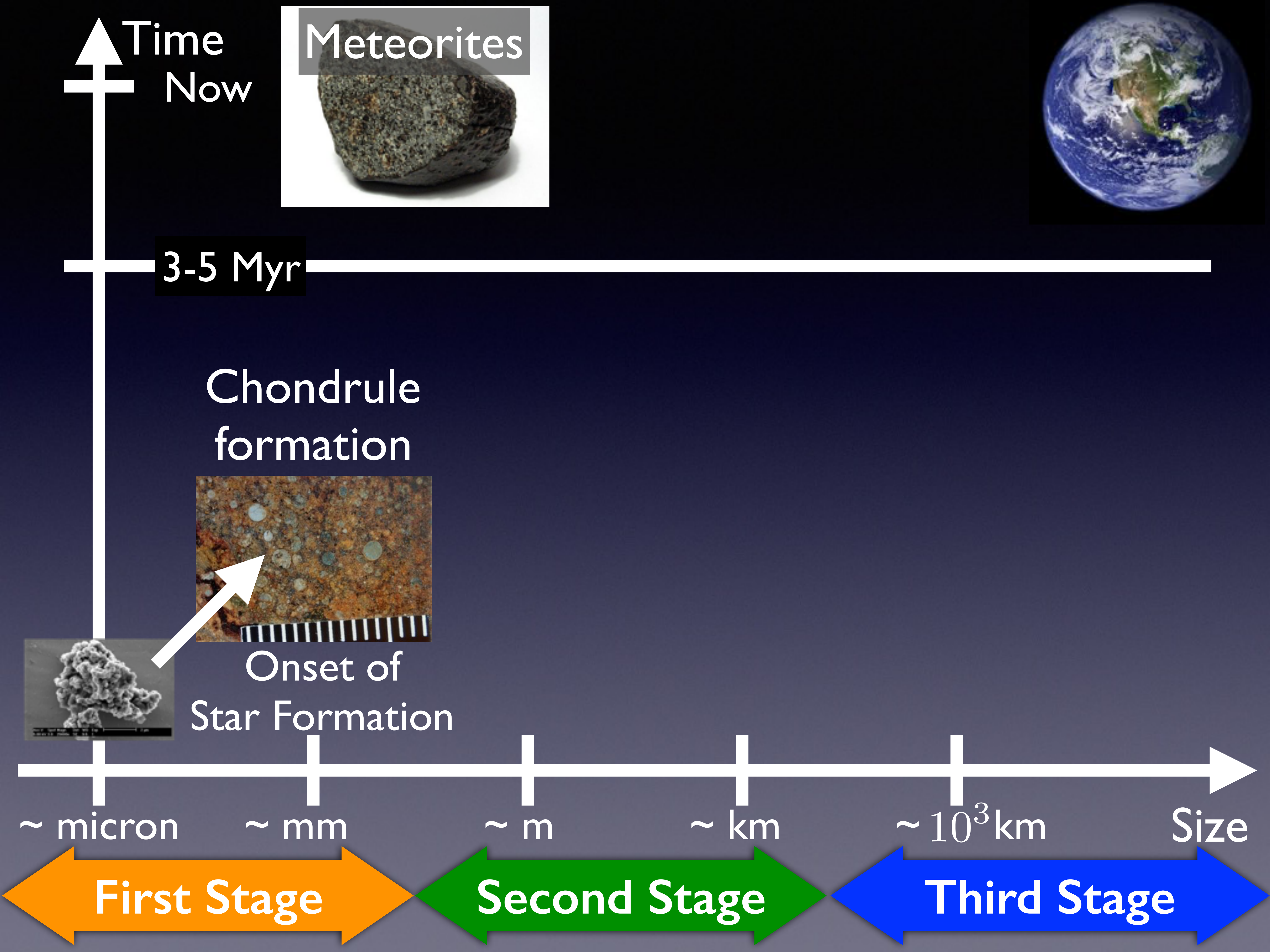
Chondrules are abundant in chondrites that are one class of meteorites

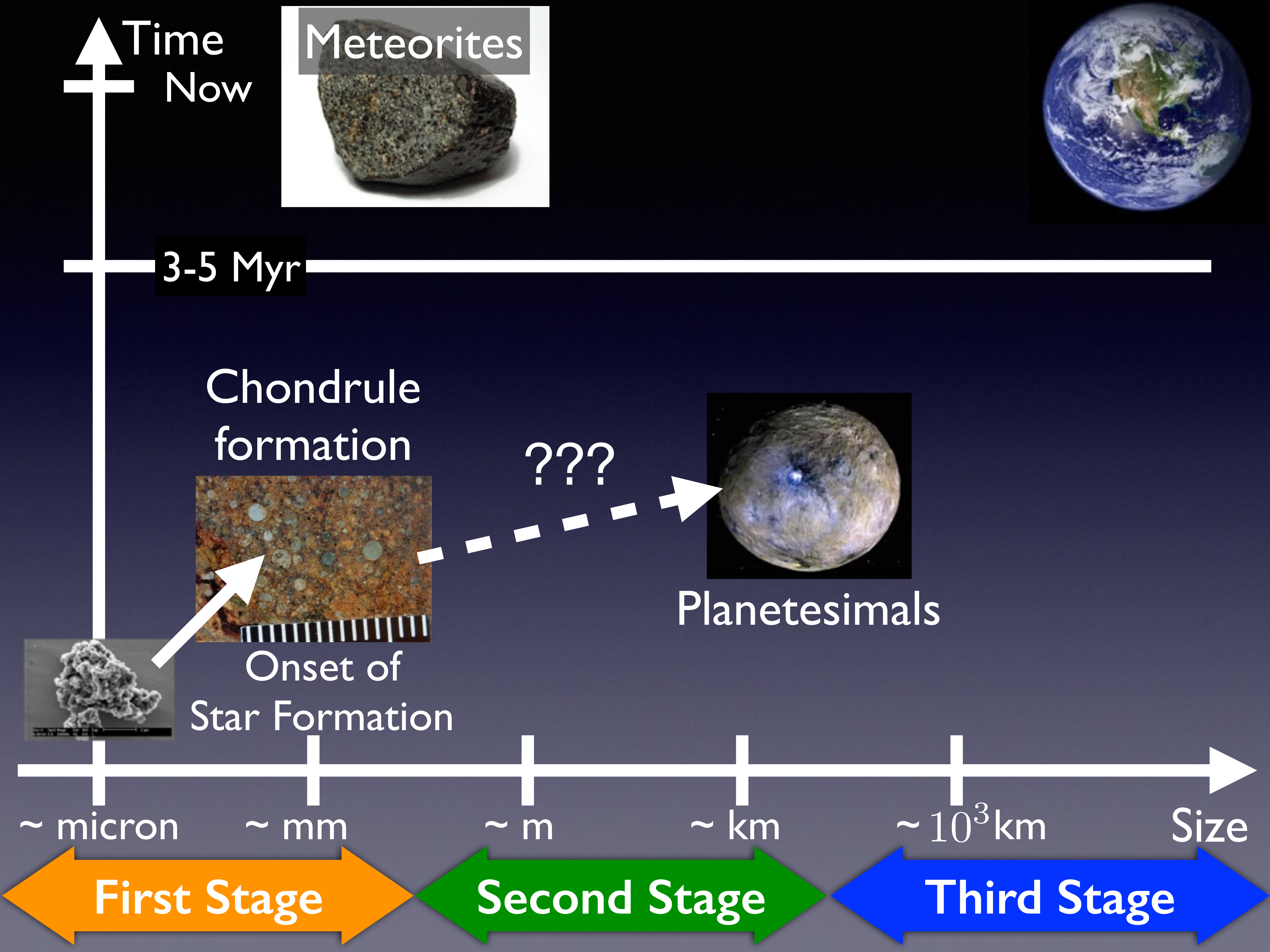
kept forming for **3-5 Myr** after CAI formation began, which is 4.567 Gyr ago

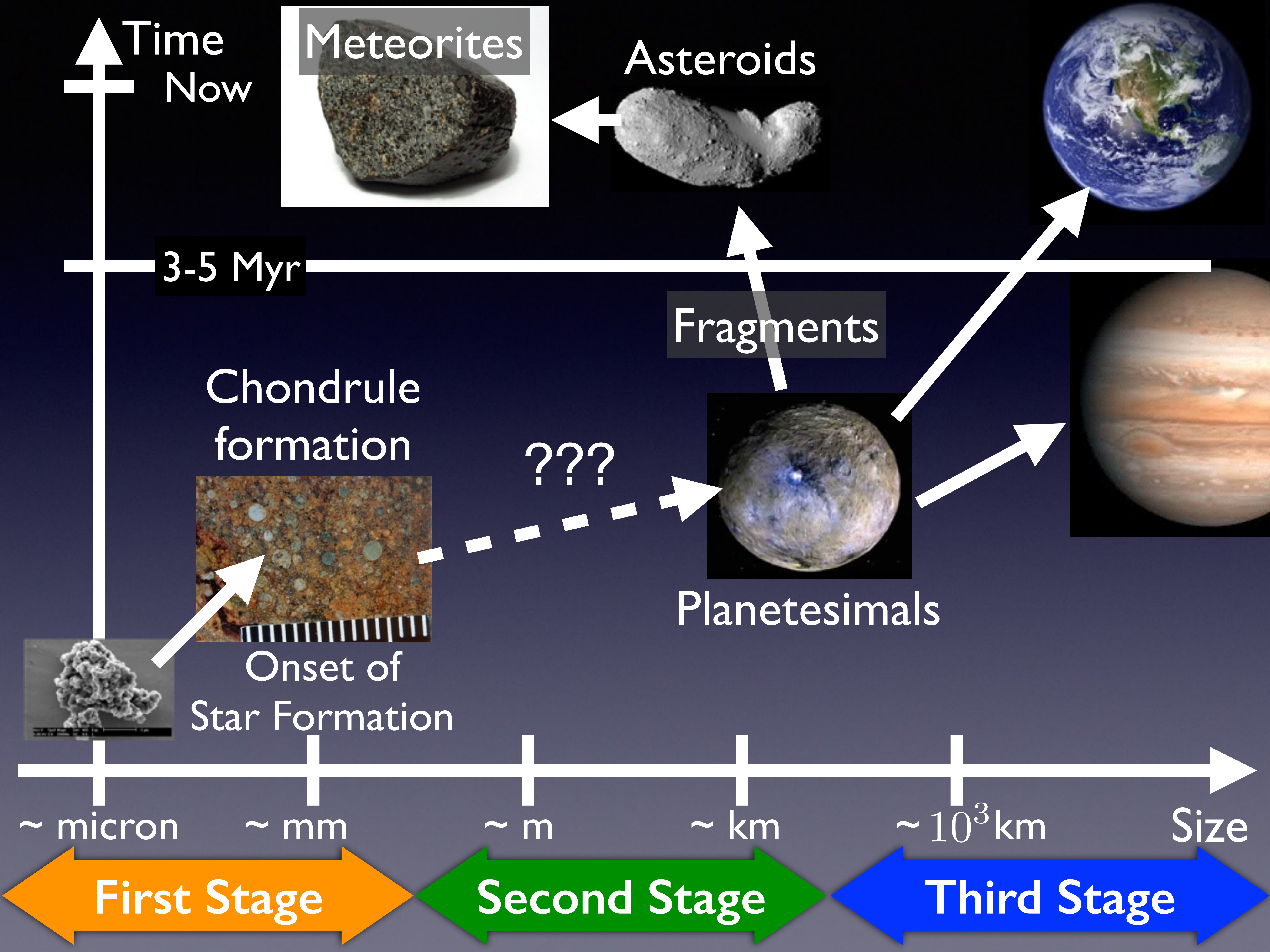

~ micron
~ mm
~ m
~ km
~ 10^3km
Size
First Stage
Second Stage
Third Stage

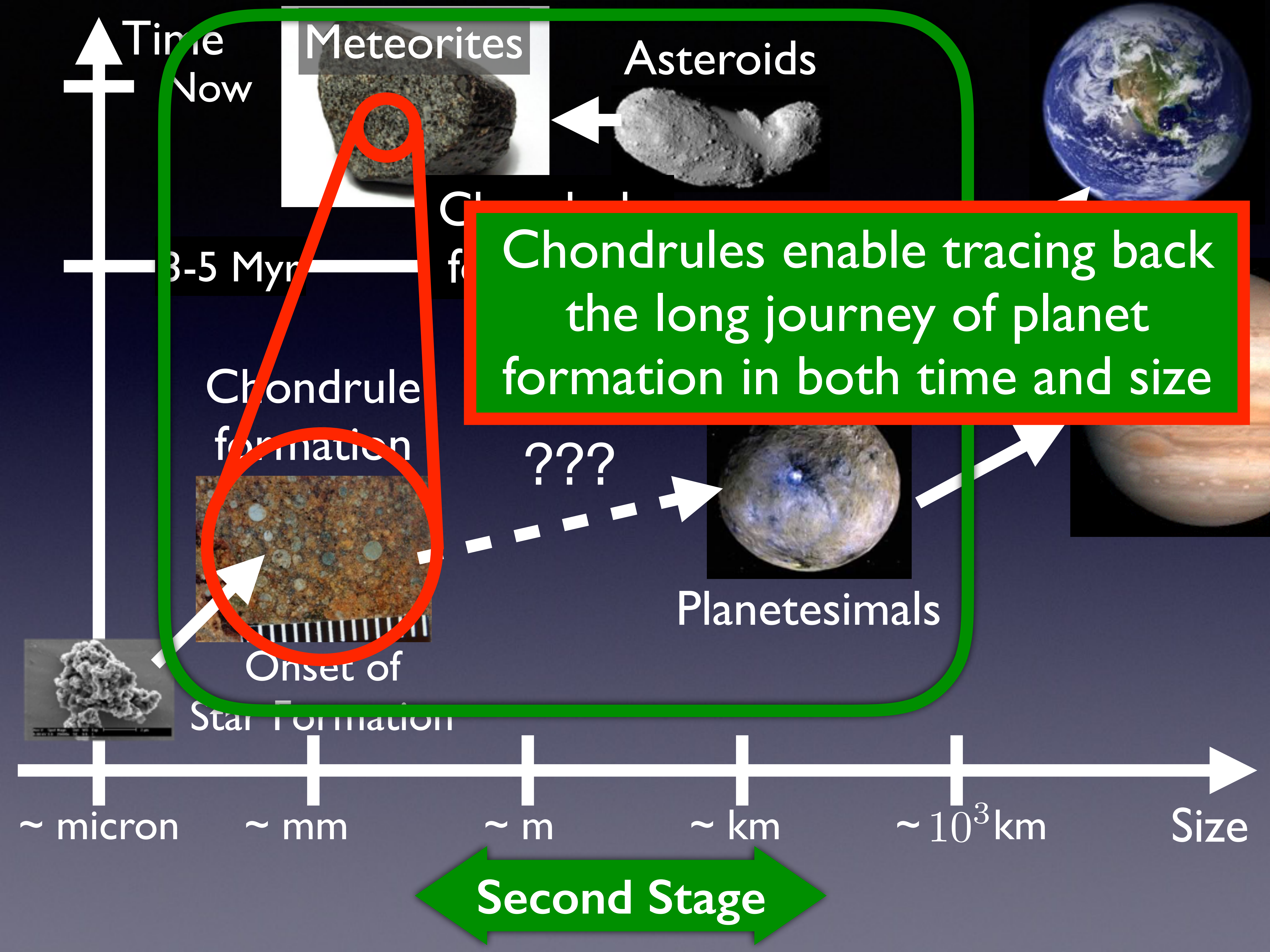


Time
Now
Meteorites
Onset of
Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
3-5 Myr
Chondrule
formation
Onset of
Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
3-5 Myr
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
Asteroids
3-5 Myr
Fragments
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage

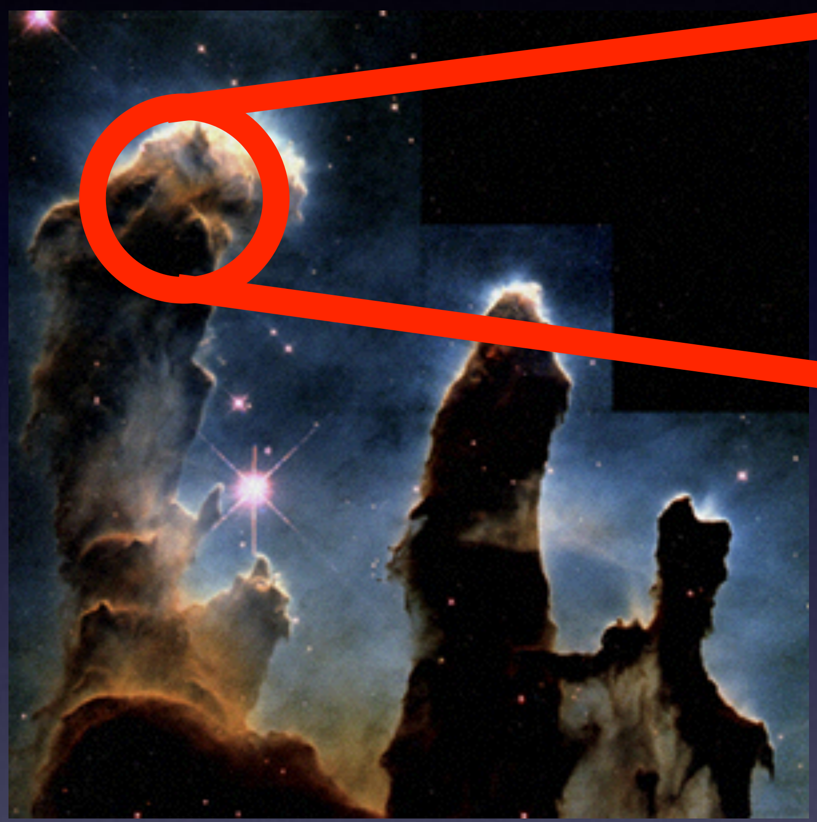


Time
Now
Meteorites
Asteroids
3-5 Myr
Chondrules enable tracing back the long journey of planet formation in both time and size
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3km
Size
Second Stage

Current Picture of Planet Formation

e.g., Hayashi 1981

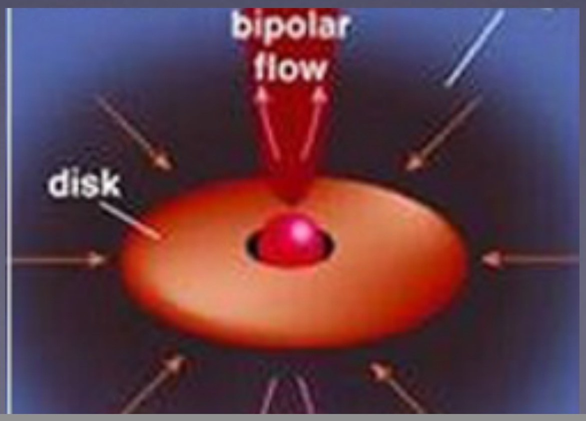
NIR image of
Hubble Space Telescope



The Eagle Nebula
(d ~ 2000 pc)

Molecular Clouds

Gravitational
collapse

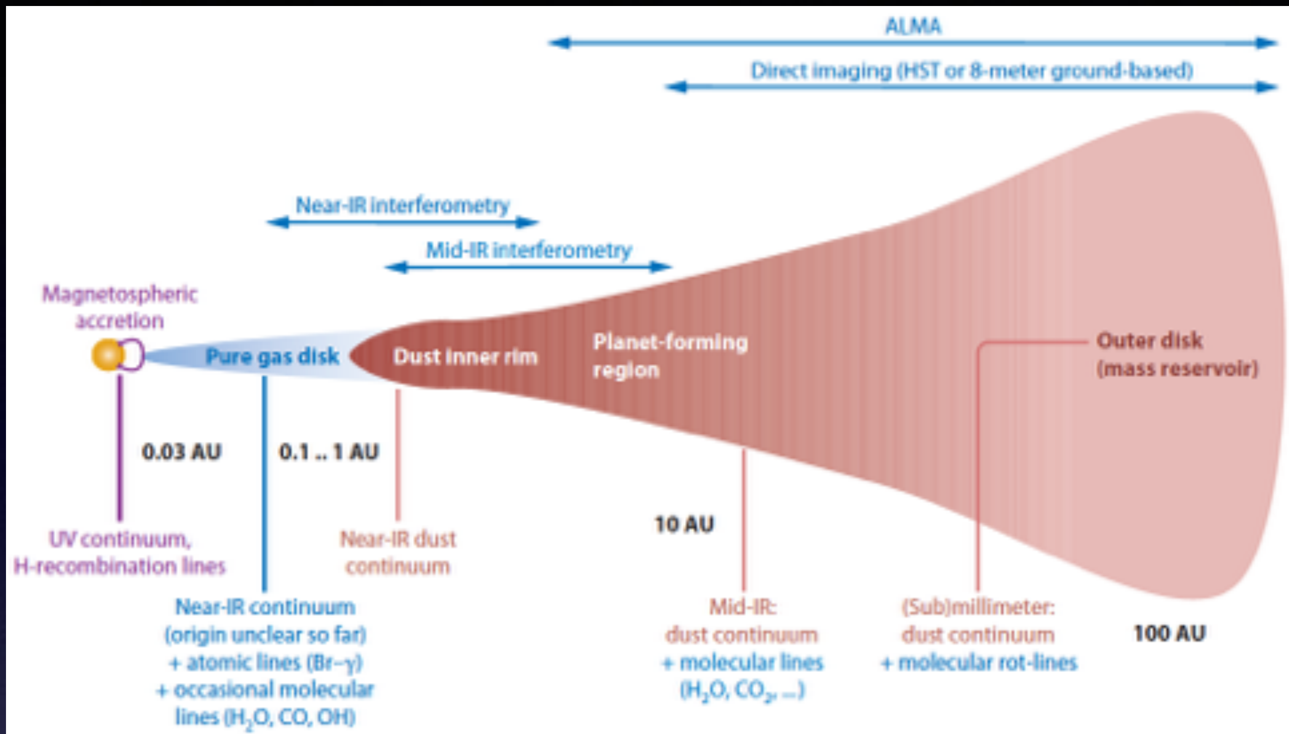


Circumstellar Disks

1 pc $= 3 \times 10^{18} cm$

Current Picture of Planet Formation

e.g., Hayashi 1981



$$M_{disk} \sim 10^{-2} M_\odot$$

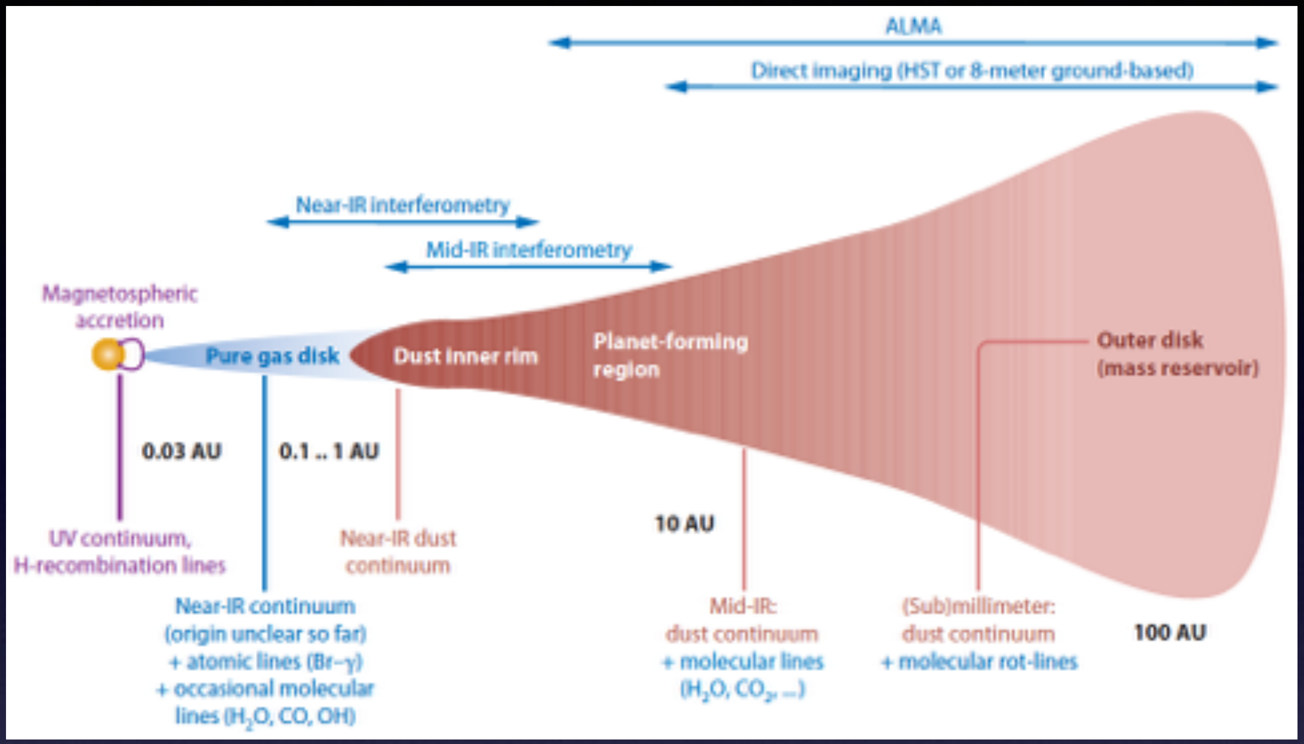
(: ~ 99% of gas and ~ 1% of dust)

$$\tau_{disk} \sim 10^6 - 10^7 yr$$

Disks are turbulent possibly by magnetic fields

Current Picture of Planet Formation

e.g., Hayashi 1981



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Disks are turbulent possibly by magnetic fields

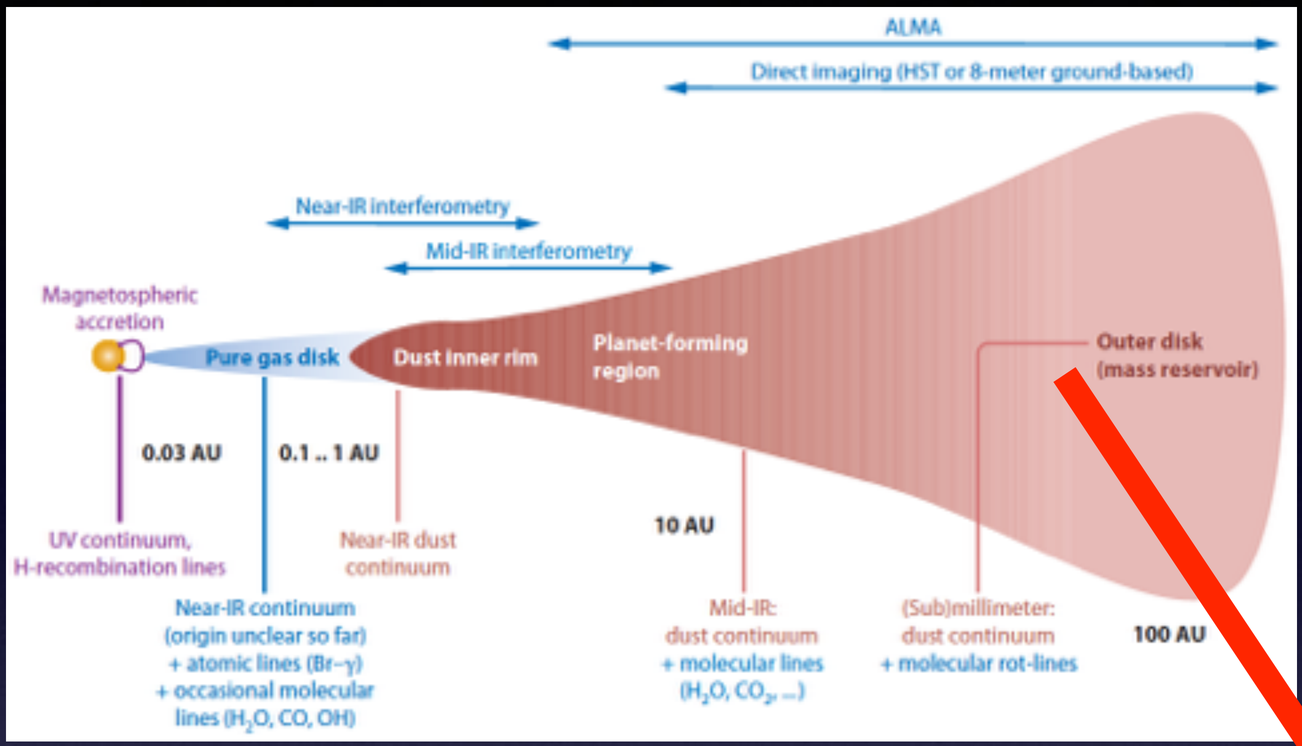
At 1 au, $n \sim 10^{14} cm^{-3}$

$$T \sim 300K$$

cf) the atmosphere of the Earth,
At 1 bar, $n \sim 10^{19} cm^{-3}$

Current Picture of Planet Formation

e.g., Hayashi 1981



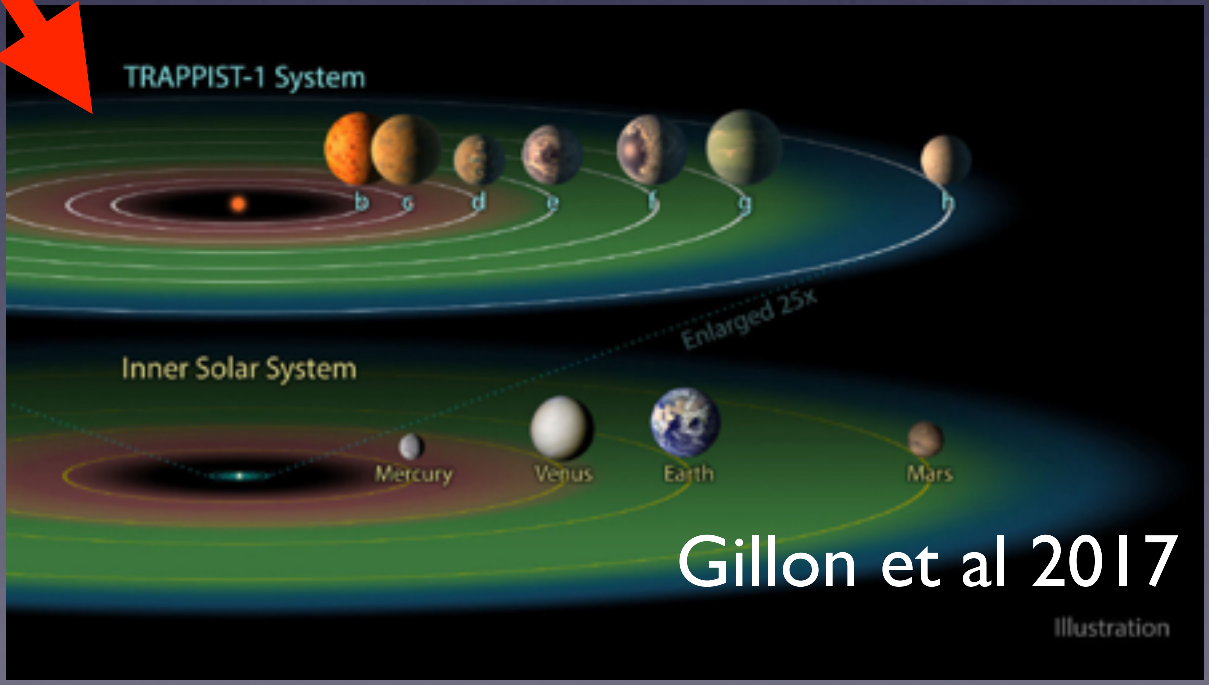
$M_{disk} \sim 10^{-2} M_{\odot}$

(: ~ 99% of gas and ~ 1% of dust)

$\tau_{disk} \sim 10^6 - 10^7 yr$

Disks are turbulent possibly by magnetic fields

10 -100 Myr



Gillon et al 2017

At 1 au, $n \sim 10^{14} cm^{-3}$

$T \sim 300K$

cf) the atmosphere of the Earth,

At 1 bar, $n \sim 10^{19} cm^{-3}$

Chondrules: the primitive material formed in the Solar Nebula (disk)

abundant in chondrites
(up to 80 % by volume)

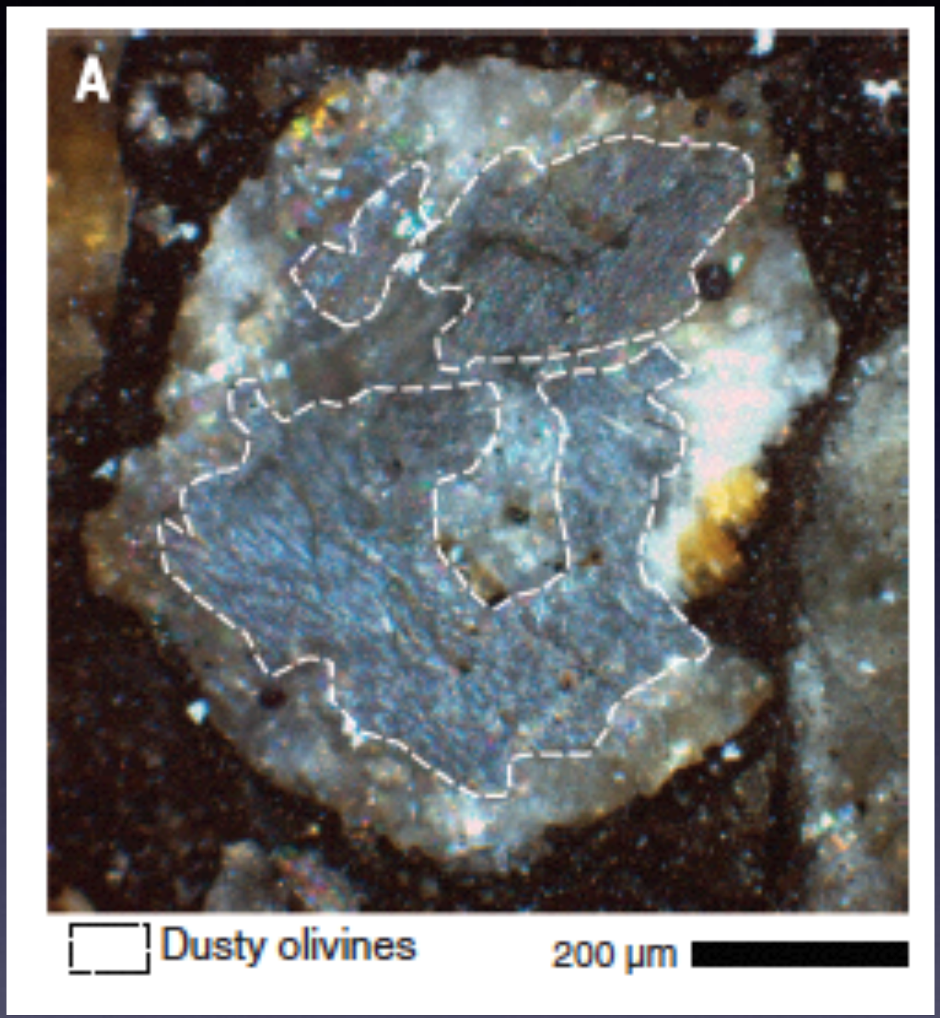
~1mm sized spherical particles
formed as molten droplets
of silicate (T ~ 1800K)

the cooling rate is
~ 10 - 1000 K per hour
(the nebular gas is needed)

kept forming for 3-5 Myr
after CAI formation began,
which is 4.567 Gyr ago

cf) Mars formed at ~2 Myr after CAI formation

New information from lab experiments : magnetic fields in the nebula (disk)



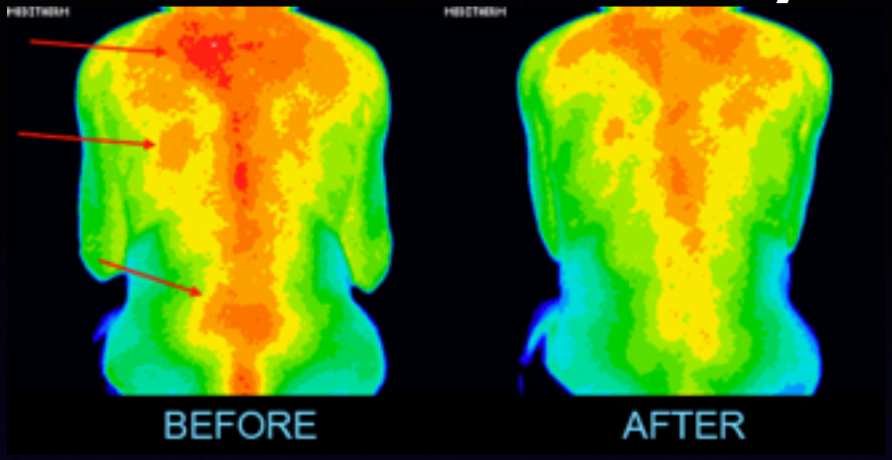
Fu et al 2014

Semarkona meteorite
: primitive, ordinary chondrite

Both thermoremanent magnetization & its direction
=> olivine-bearing chondrules were magnetized in the solar nebula

B-fields in the solar nebula were ~ 50 - 540 mG
=> Level of turbulence in the nebula can be estimated!!

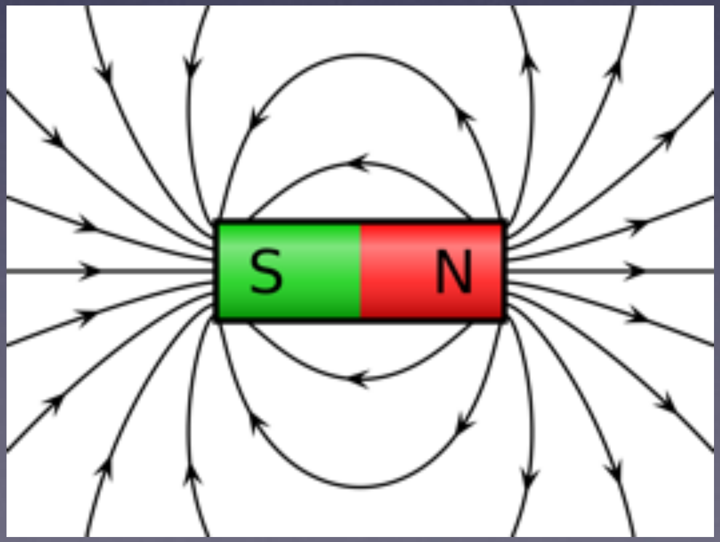
Thermal History



Abundance

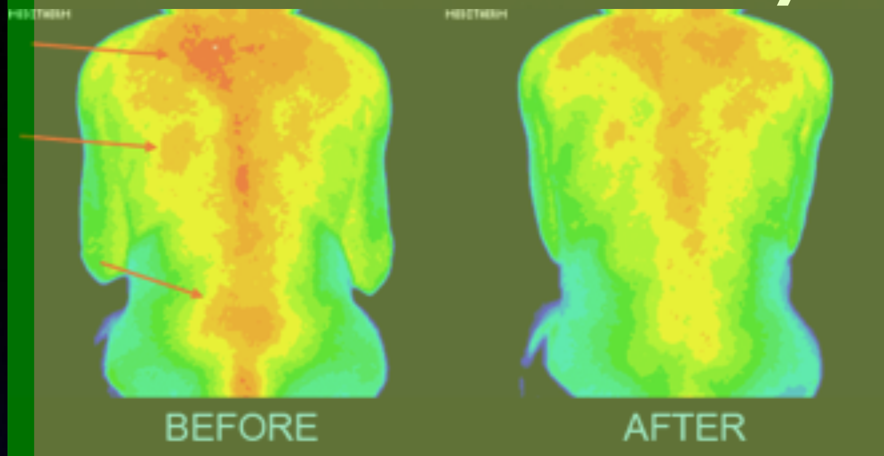
Chondrule Formation
& Accretion

Timescale



B-fields

Thermal History

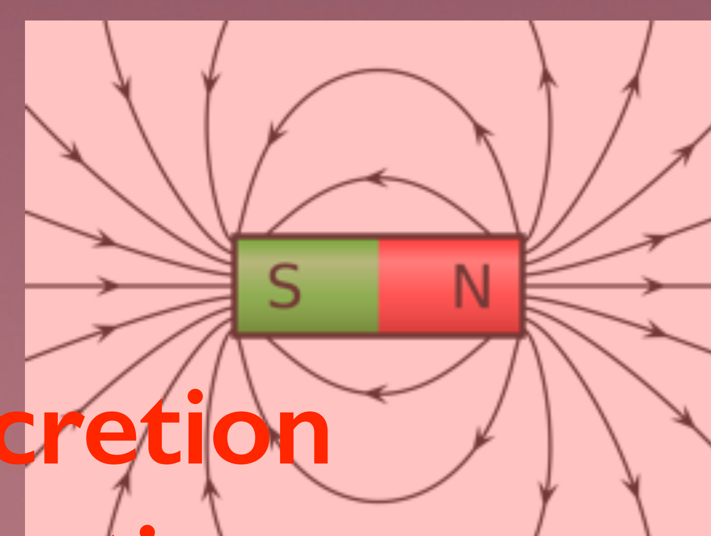


Abundance

Chondrule Formation
& Accretion

Chondrule Formation
= Impact Jetting

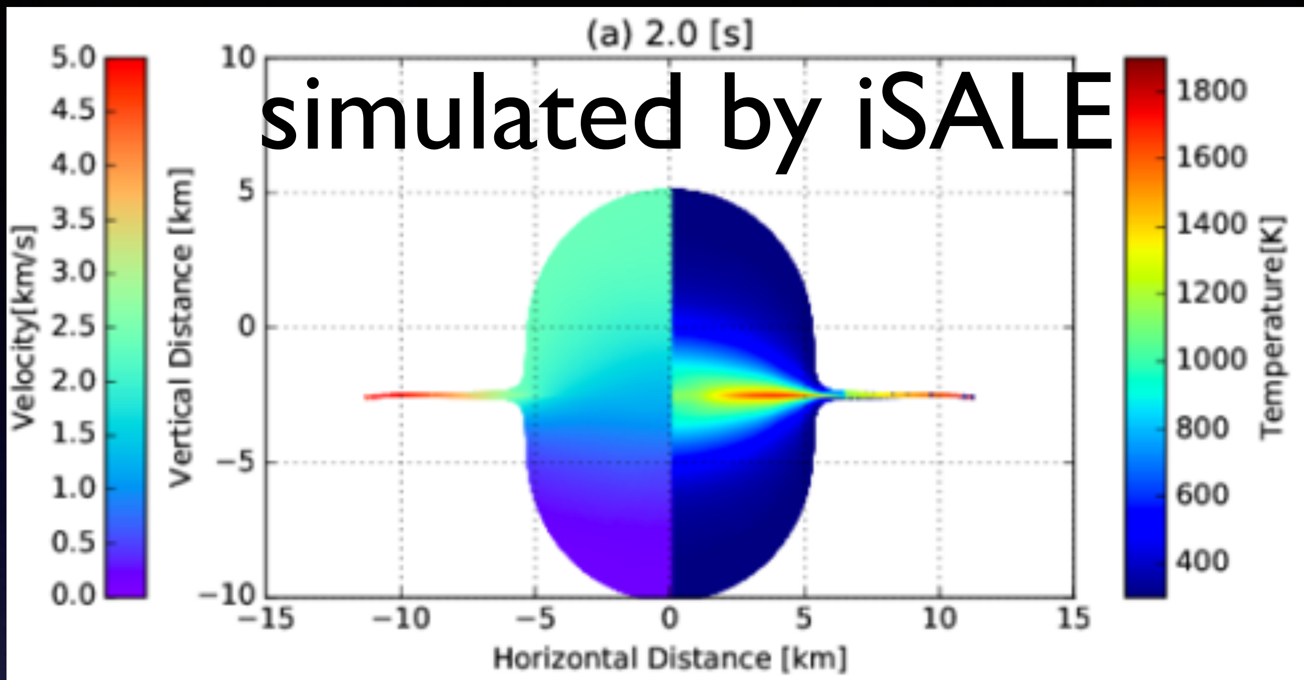
Timescale



Chondrule Accretion
= Pebble Accretion

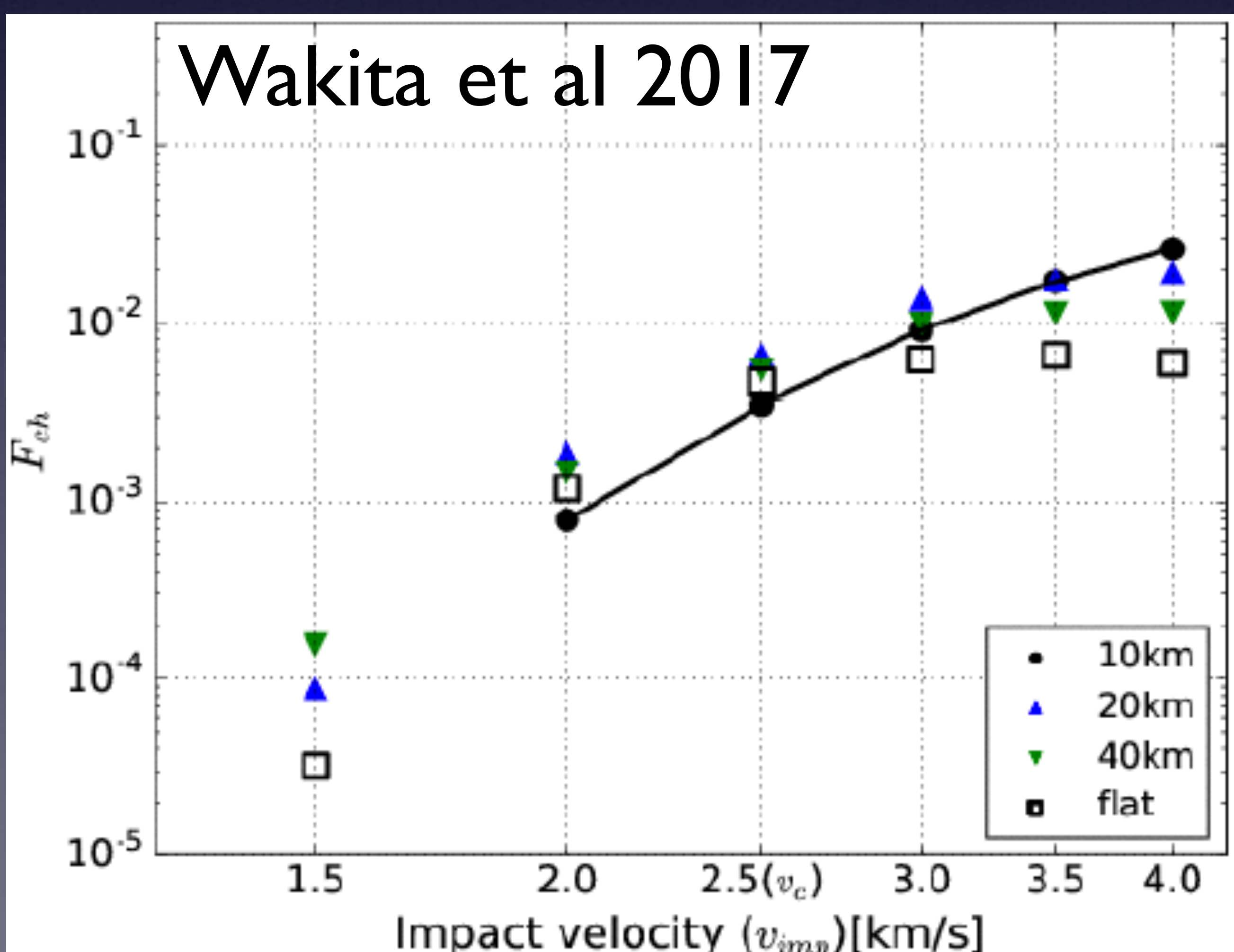
B-fields

Key idea: impact jetting



e.g., Johnson et al 2015

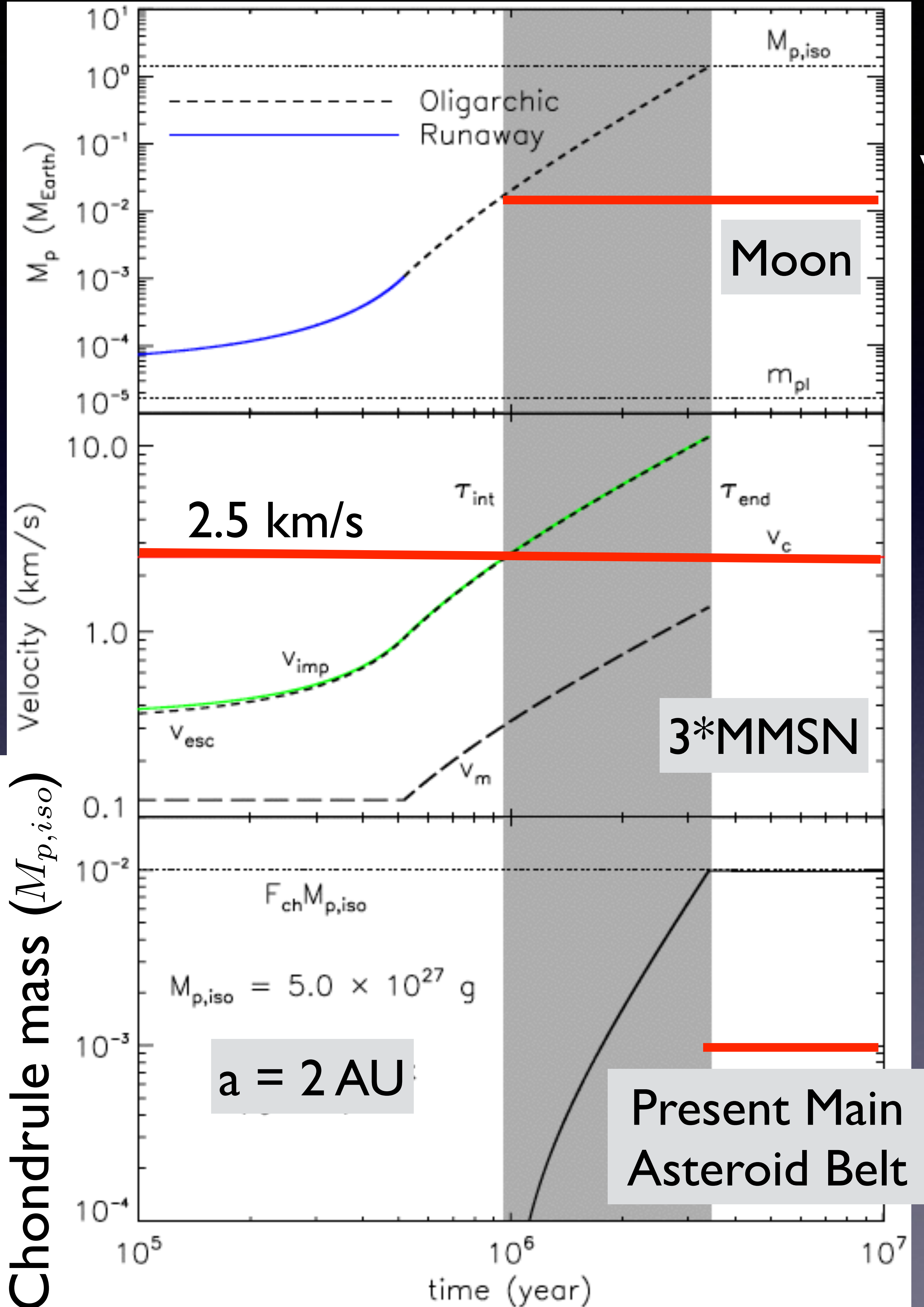
A planetesimal with r = 5km collides with a planetesimal or a protoplanet



Some materials melt, and are ejected from the system

Such ejected materials may be a progenitor of chondrules

Total ejected mass is about 1% of impactors' mass when v > 2.5 km/s



Lots of collisions occur when protoplanets form

Hasegawa et al 2016a

Protoplanets form via runaway/oligarchic growth

Impact velocity of 2.5 km/s is achieved in the oligarchic pha

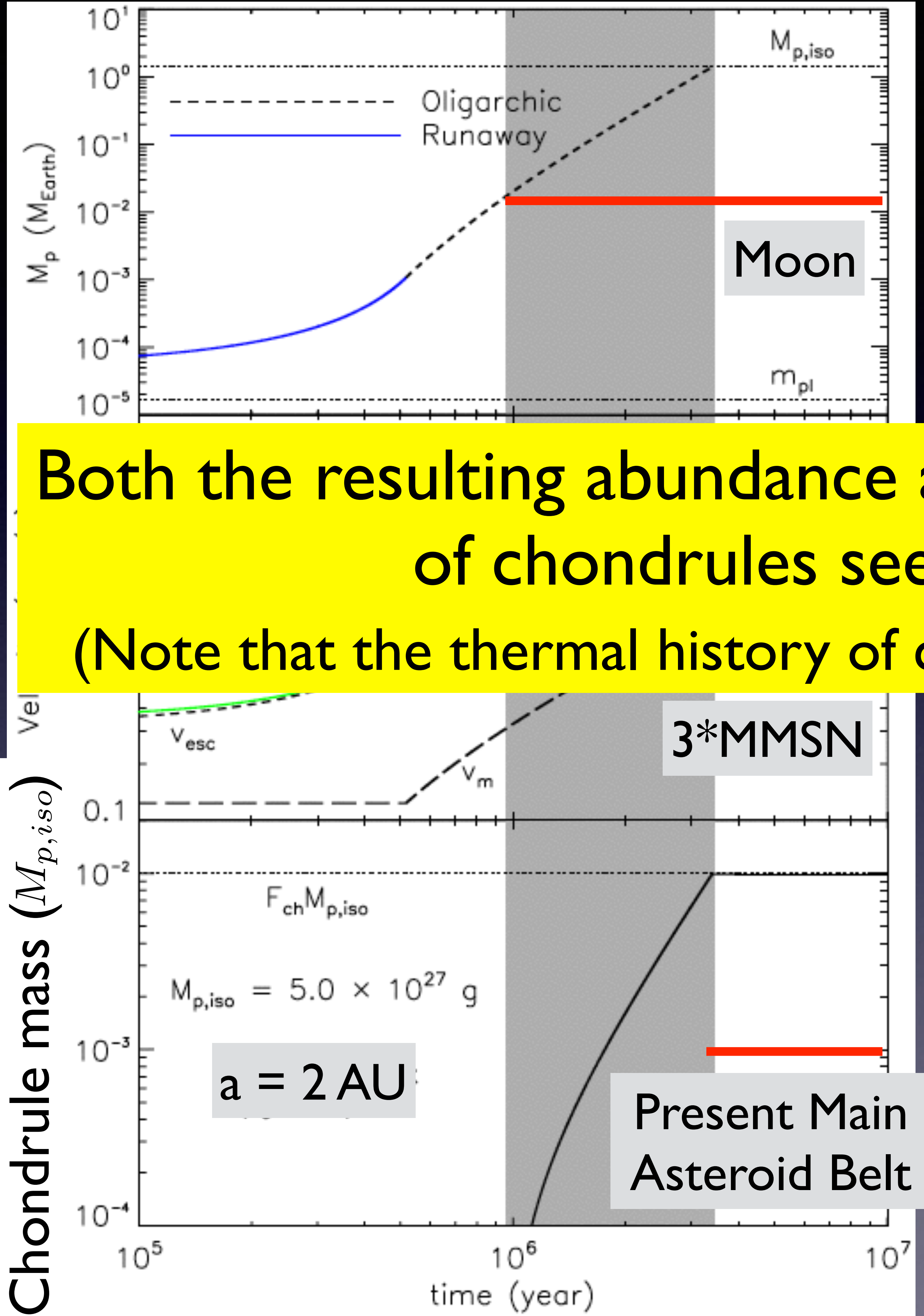
Chondrule-forming collisions occur at the hatched region

The total chondrule abundance is 1 % of the protoplanet mass

MMSN = the Minimum Mass of the Solar Nebula

Lots of collisions occur when protoplanets form

Hasegawa et al 2016a



Protoplanets form via

Both the resulting abundance and the formation timescale of chondrules seem reasonable!!

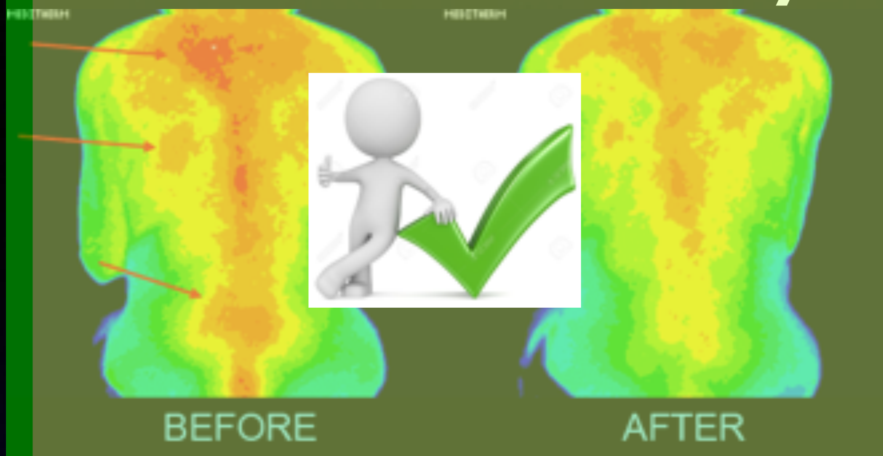
(Note that the thermal history of chondrules is also probably fine)

Chondrule-forming collisions occur at the hatched region

The total chondrule abundance is 1 % of the protoplanet mass

MMSN = the Minimum Mass of the Solar Nebula

Thermal History



Abundance

Chondrule Formation & Accretion

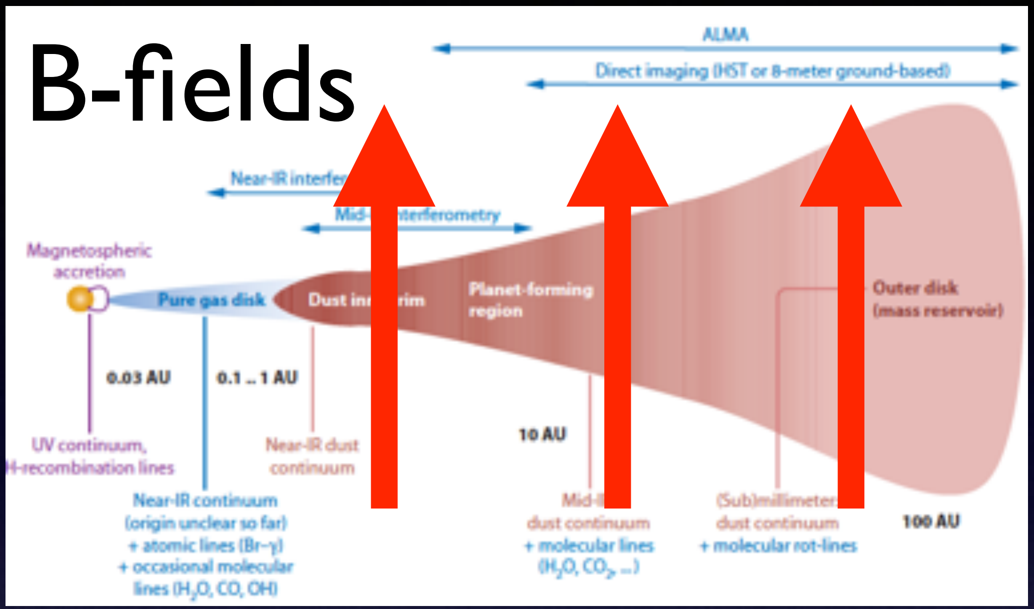
Chondrule Formation = Impact Jetting

Timescale

B-fields

Chondrule Accretion = Pebble Accretion

Lab results (magnetic fields) come into play!!!



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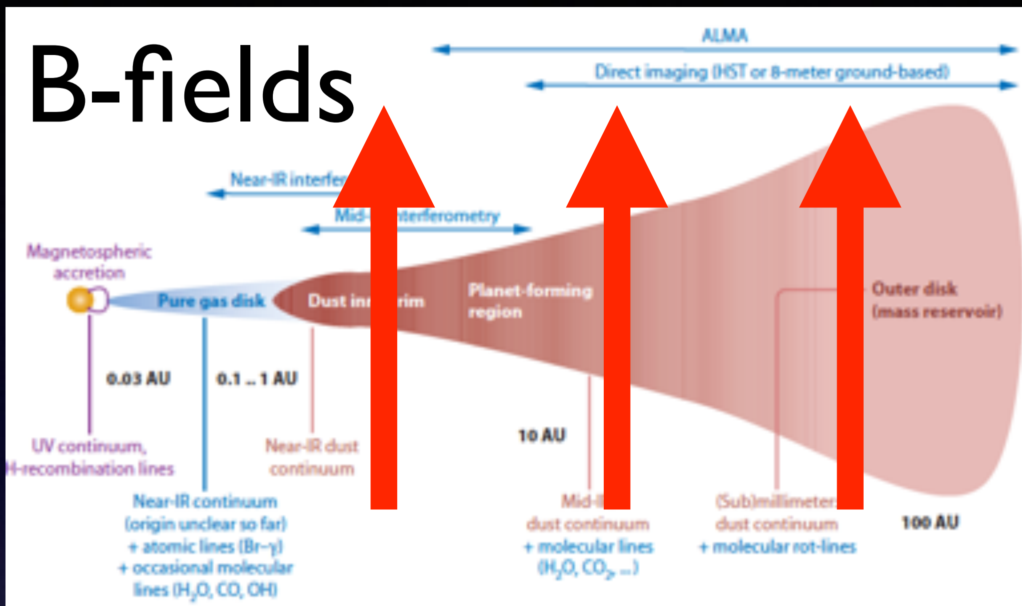
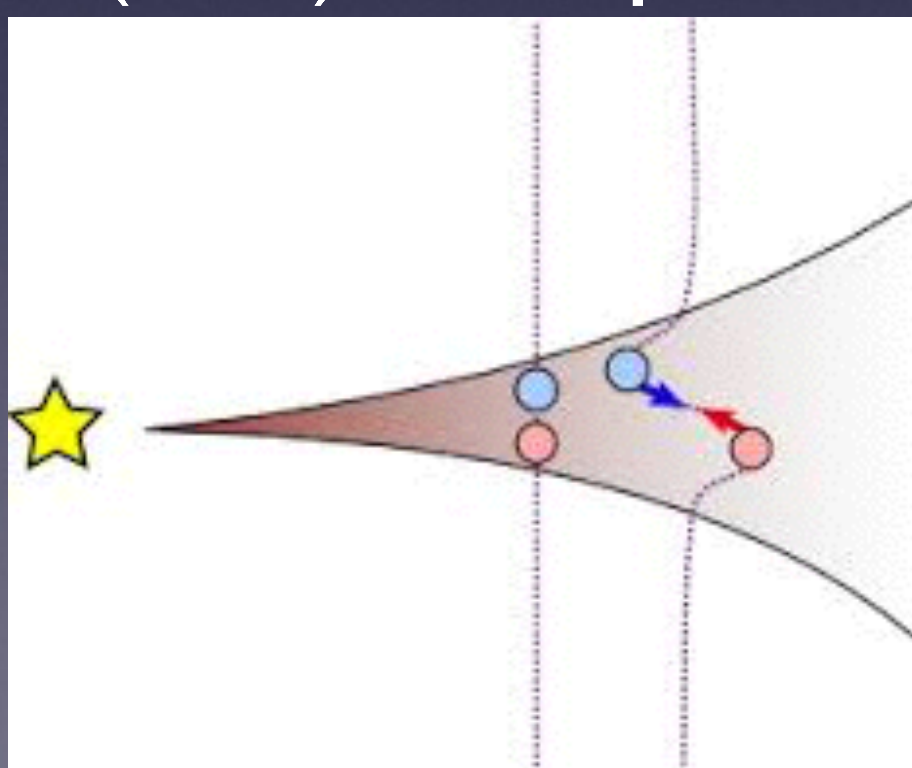
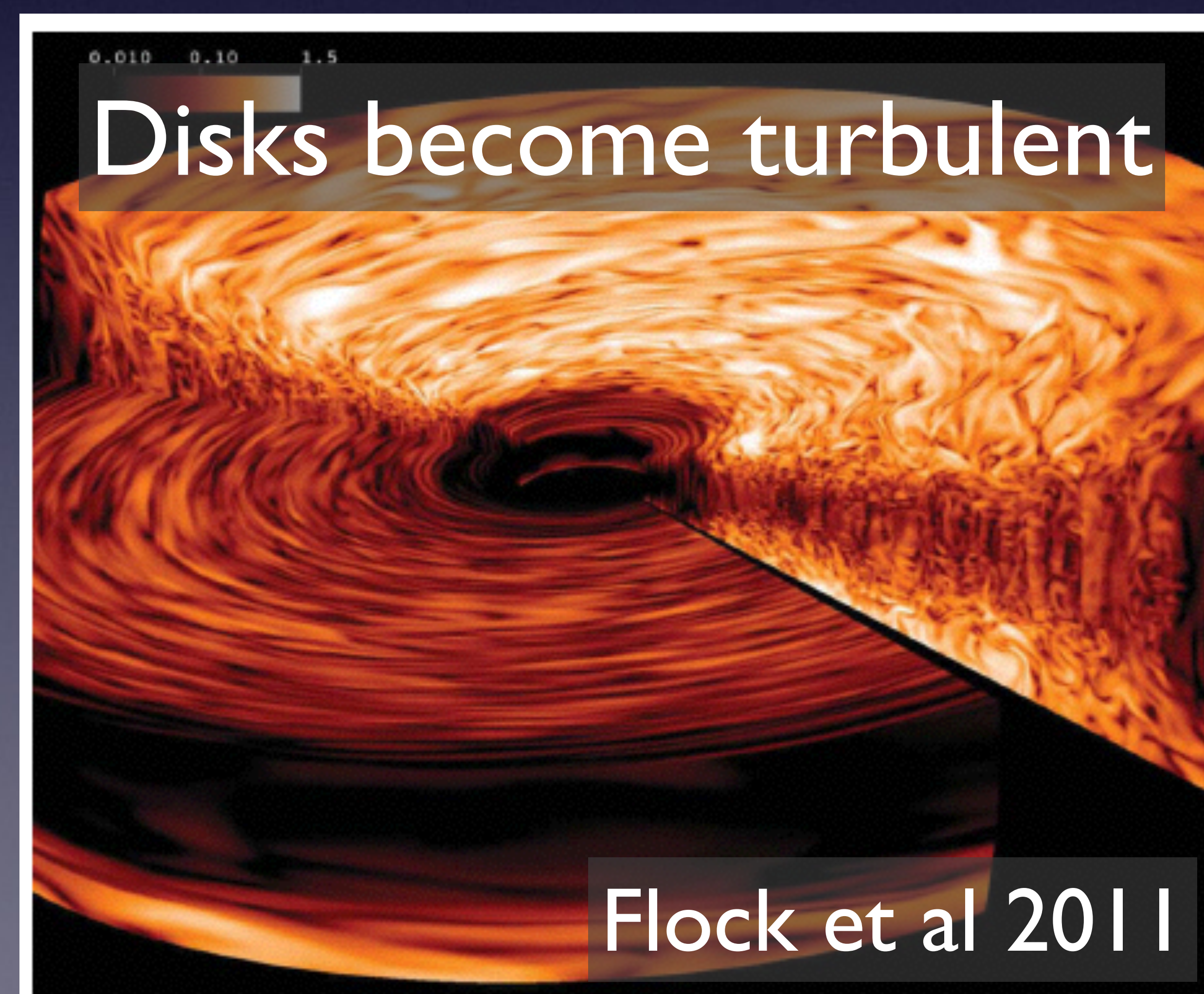


MagnetoRotational Instability (MRI) can operate





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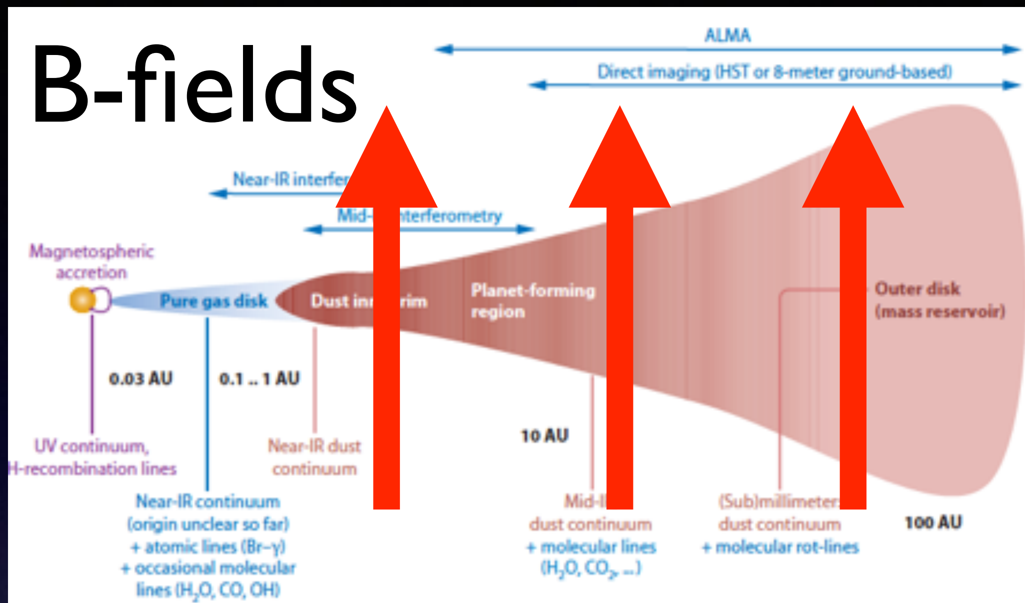
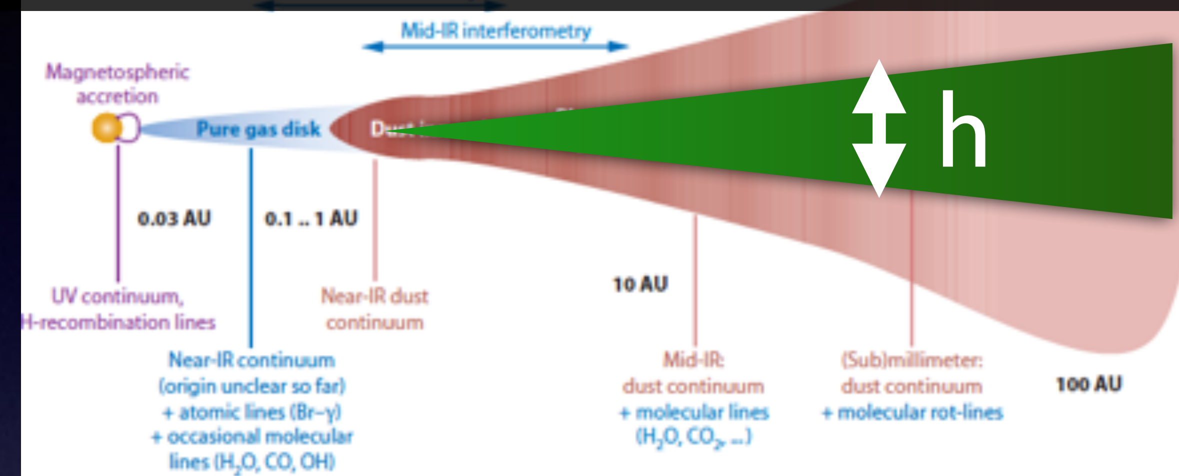
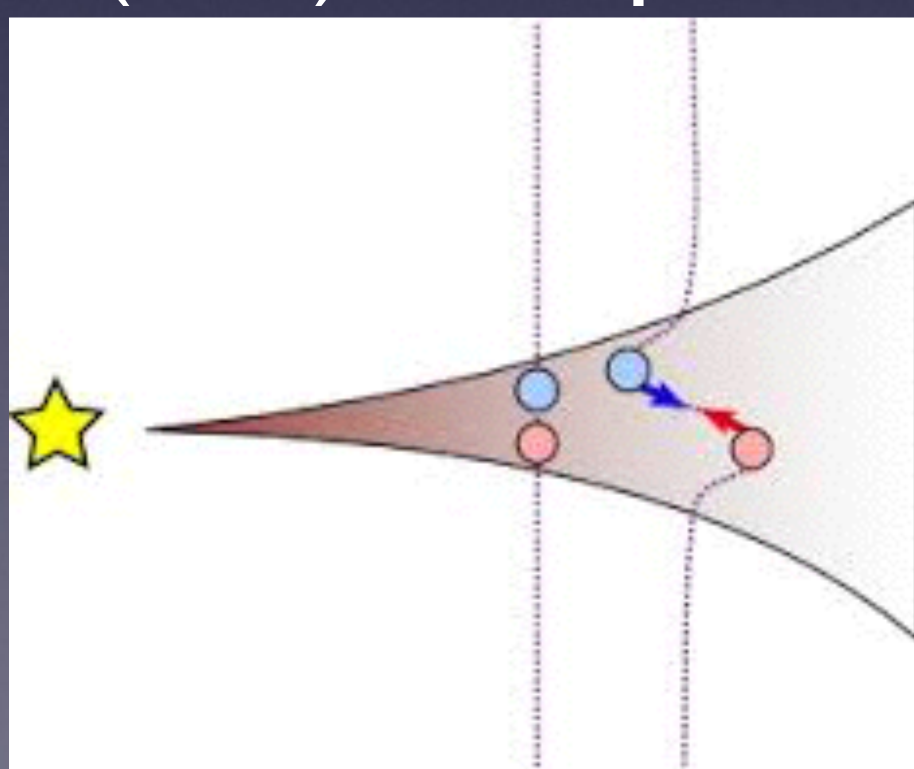
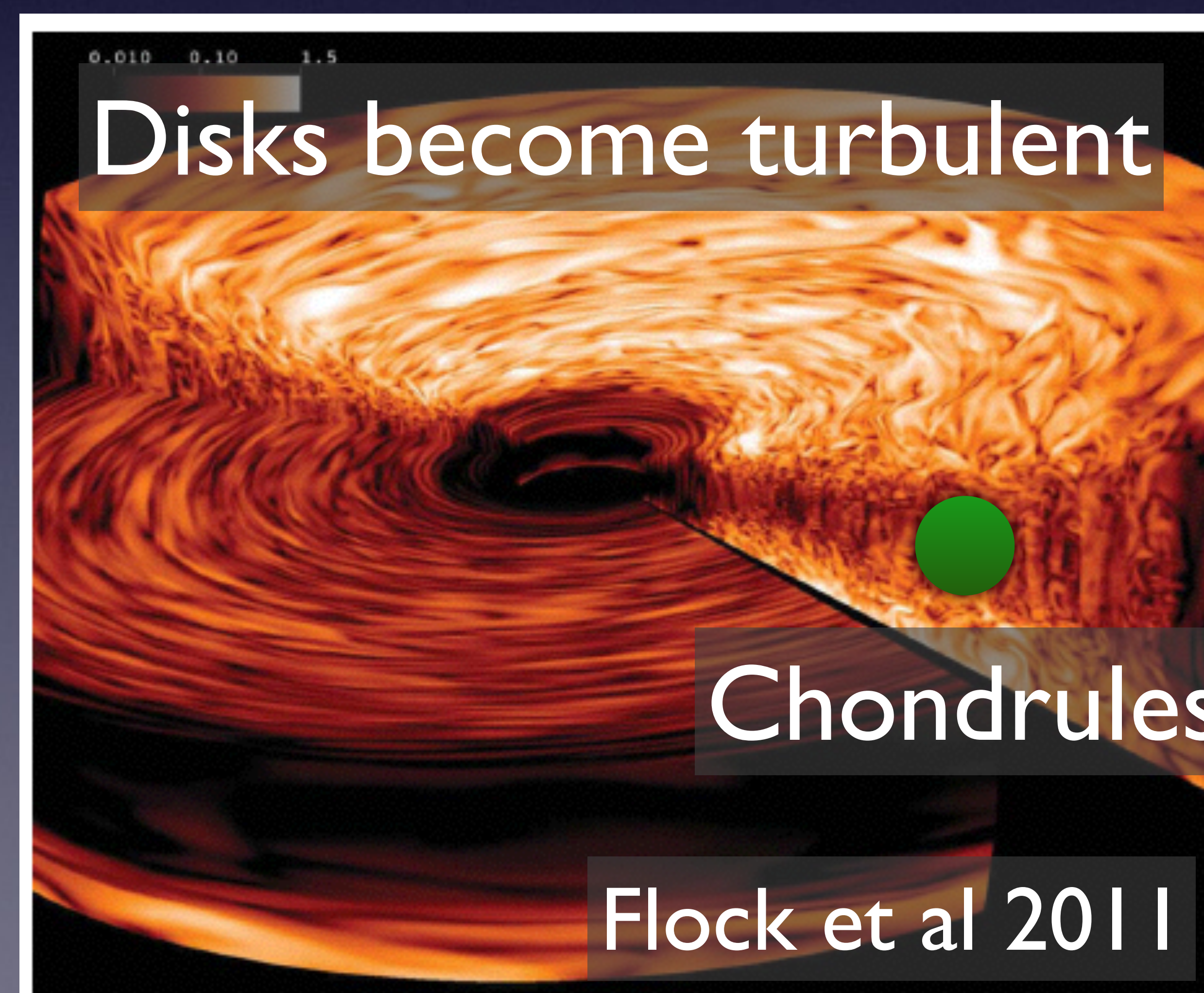


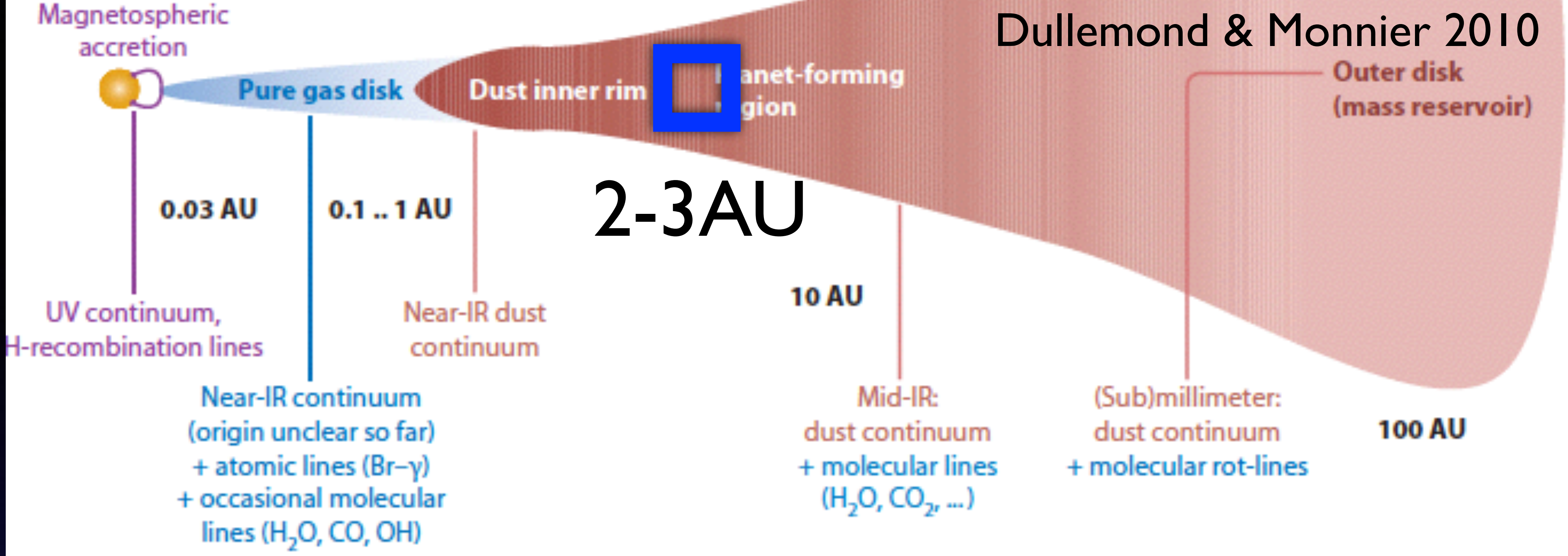
h depends on level of turbulence, so the B-field strength



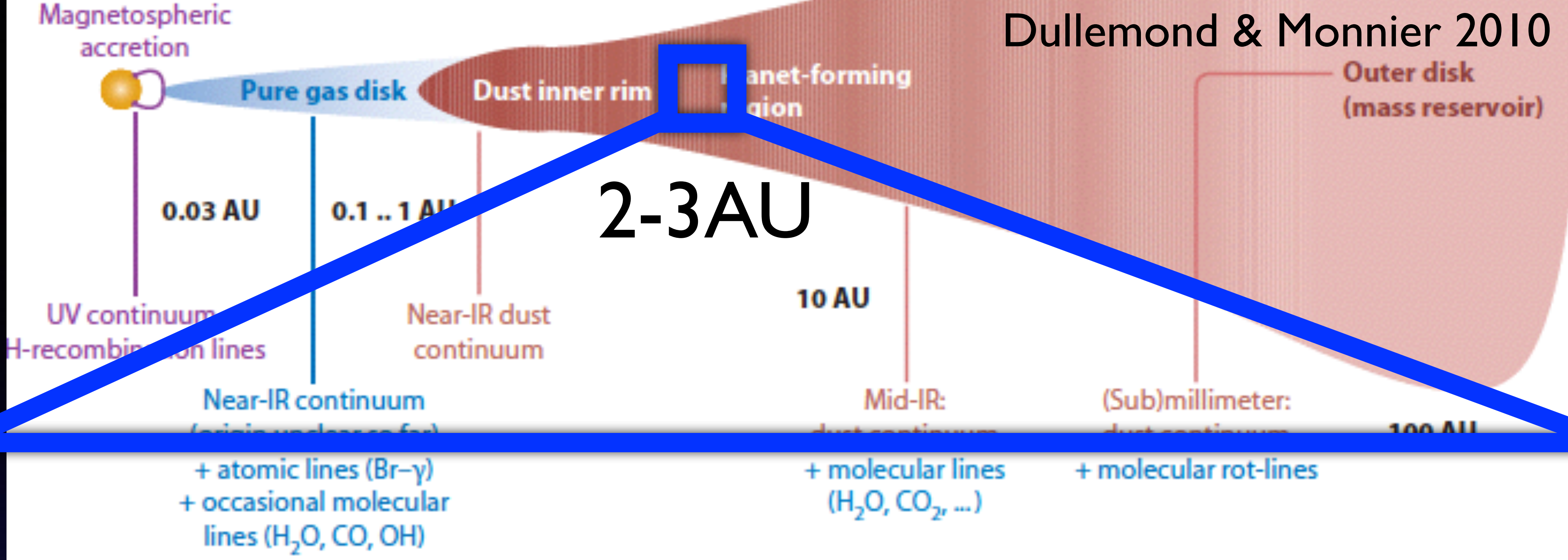
MagnetoRotational Instability (MRI) can operate



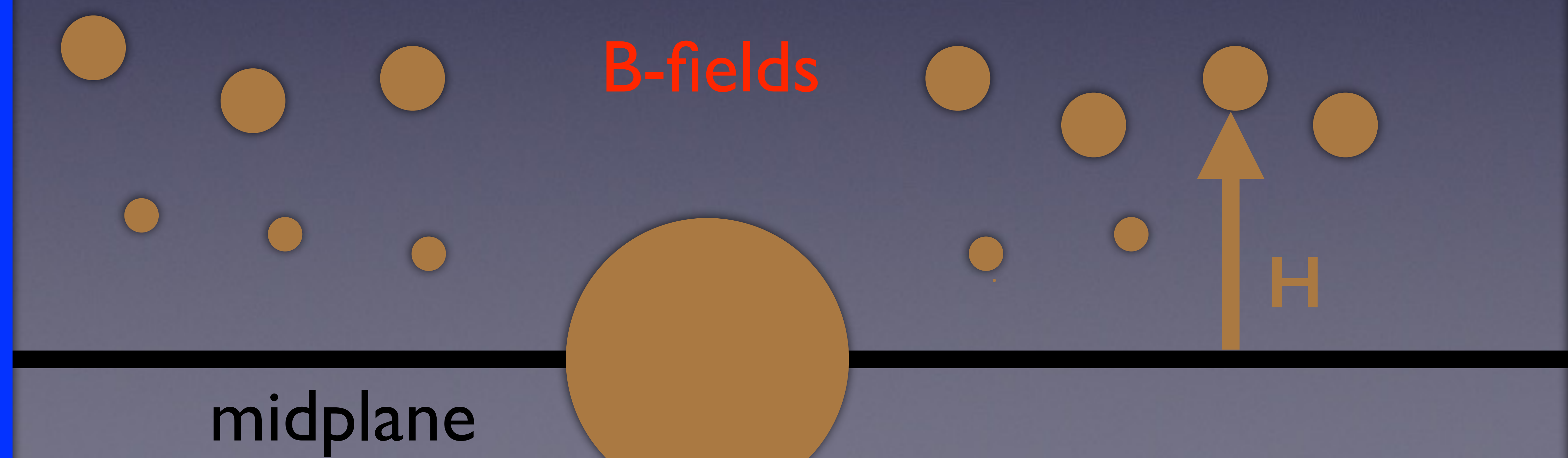


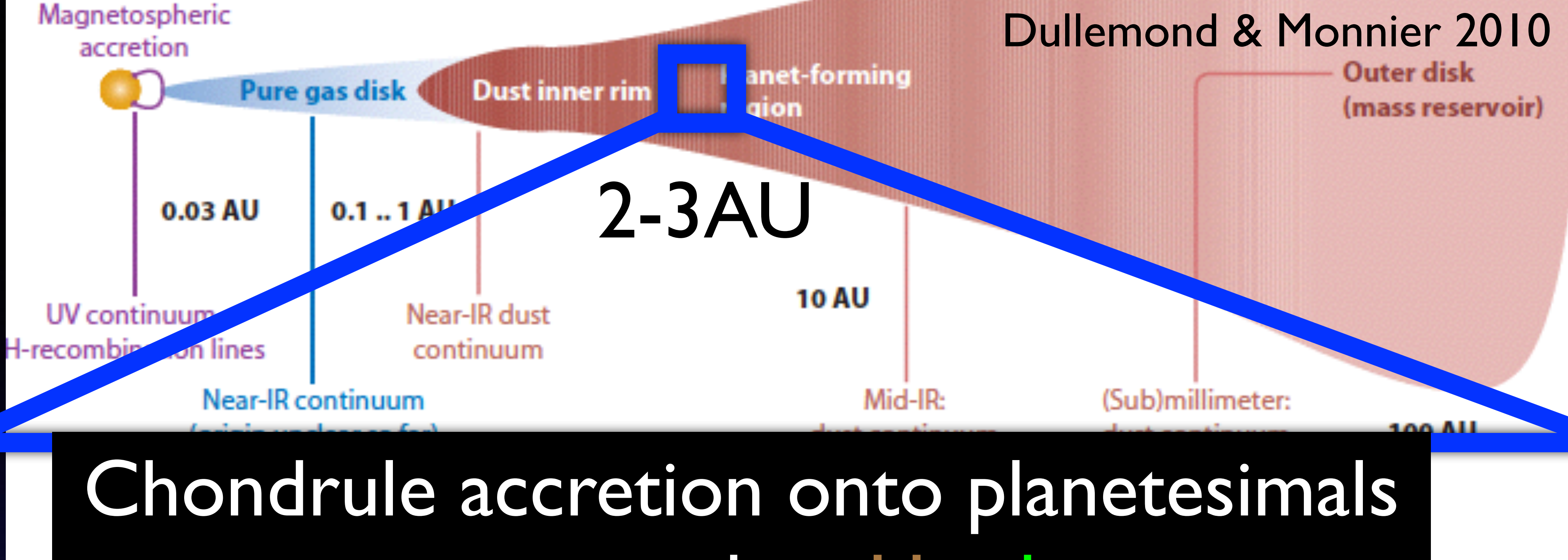

Dullemond & Monnier 2010
Magnetospheric accretion
Pure gas disk
Dust inner rim
anet-forming
gion
Outer disk (mass reservoir)
0.03 AU
0.1 .. 1 AU
2-3AU
10 AU
100 AU
UV continuum, H-recombination lines
Near-IR dust continuum
Near-IR continuum (origin unclear so far) + atomic lines (Br–γ) + occasional molecular lines (H_2O, CO, OH)
Mid-IR: dust continuum + molecular lines (H_2O, CO_2, ...)
(Sub)millimeter: dust continuum + molecular rot-lines

Dullemond & Monnier 2010



H increases with disk mass and planetesimal mass (protoplanet)



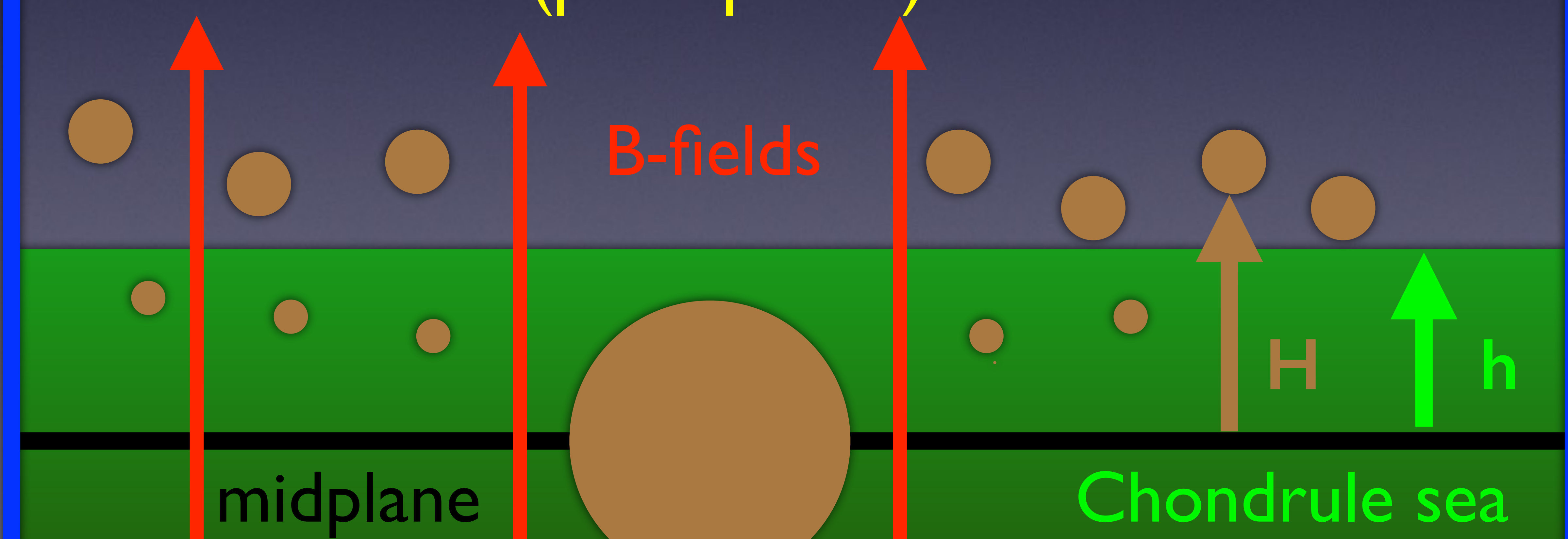


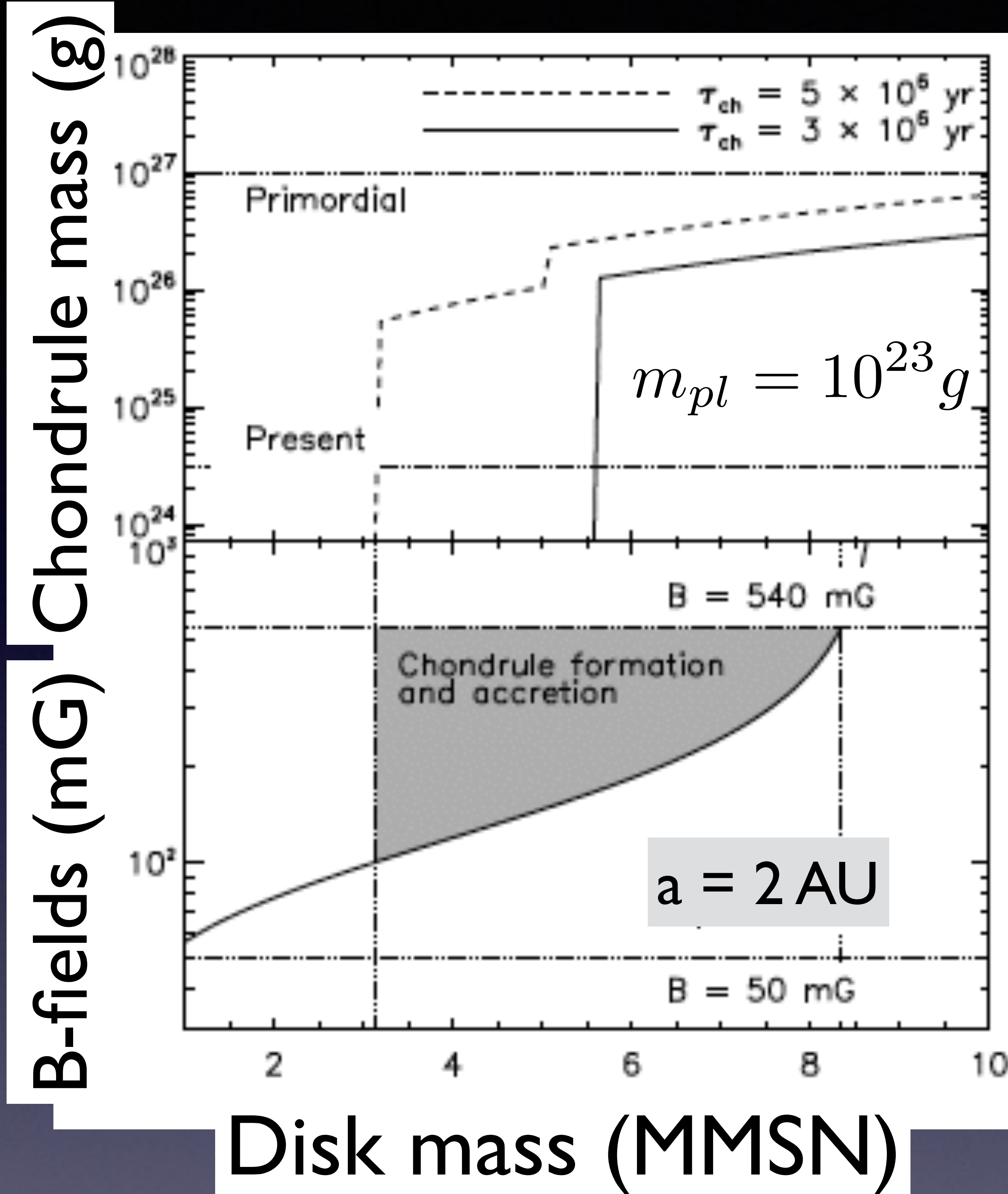
Chondrule accretion onto planetesimals occurs when H < h

Lesion et al 2015

h increases with vertical magnetic flux

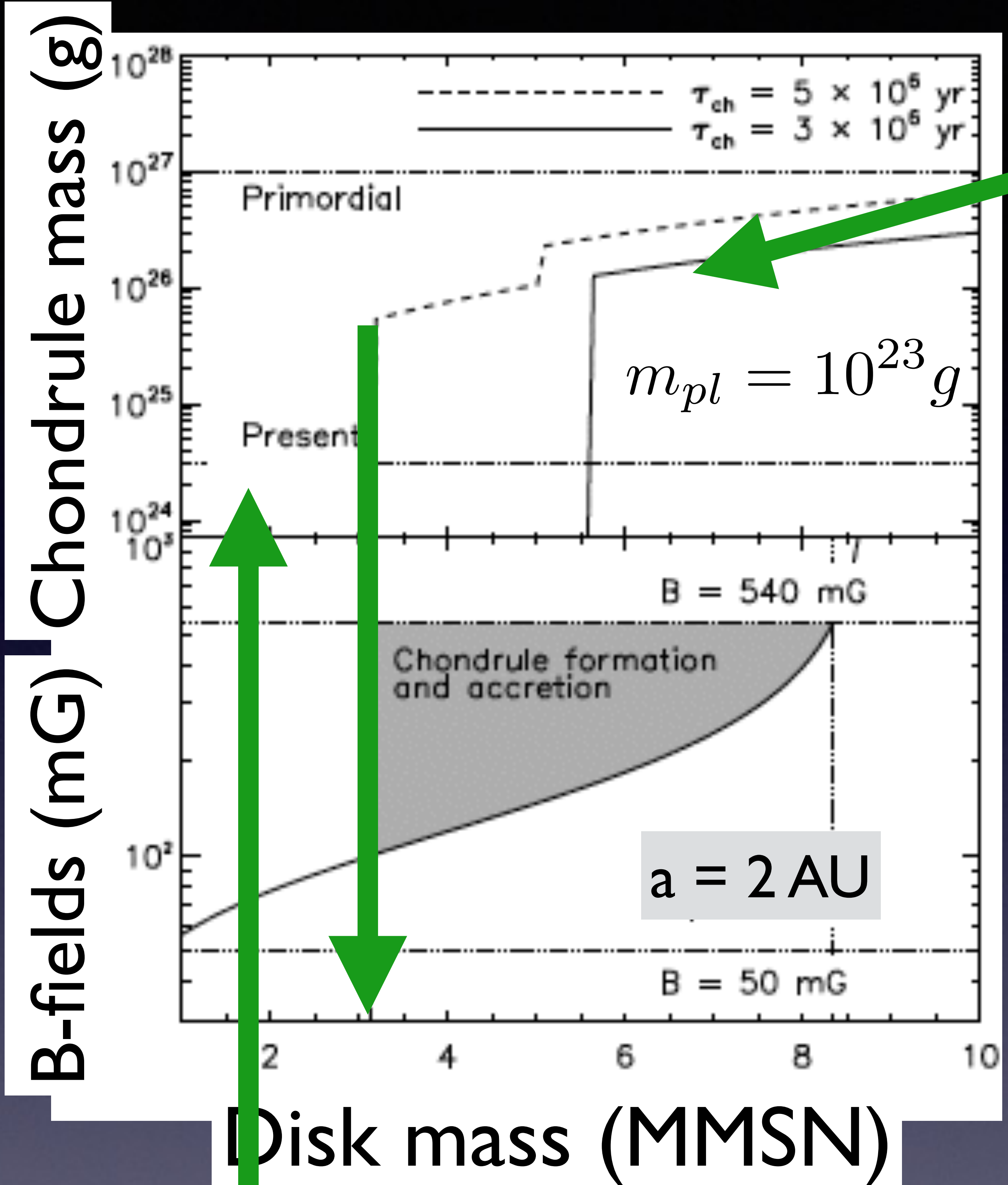
H increases with disk mass and planetesimal mass (protoplanet)





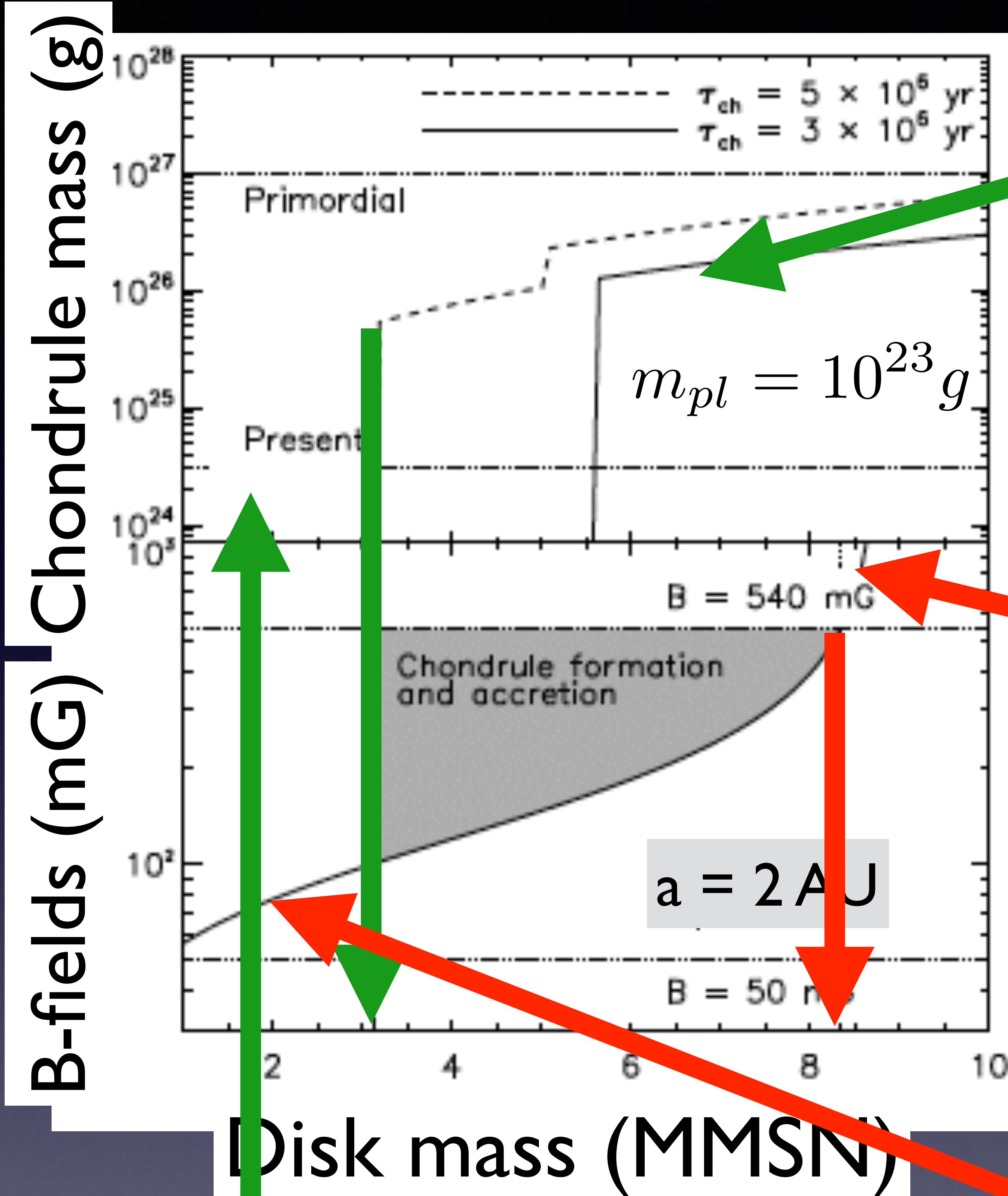
Hasegawa et al 2016b

A large number of chondrules form in massive disks



No chondrule formation due to a low disk mass

Hasegawa et al 2016b



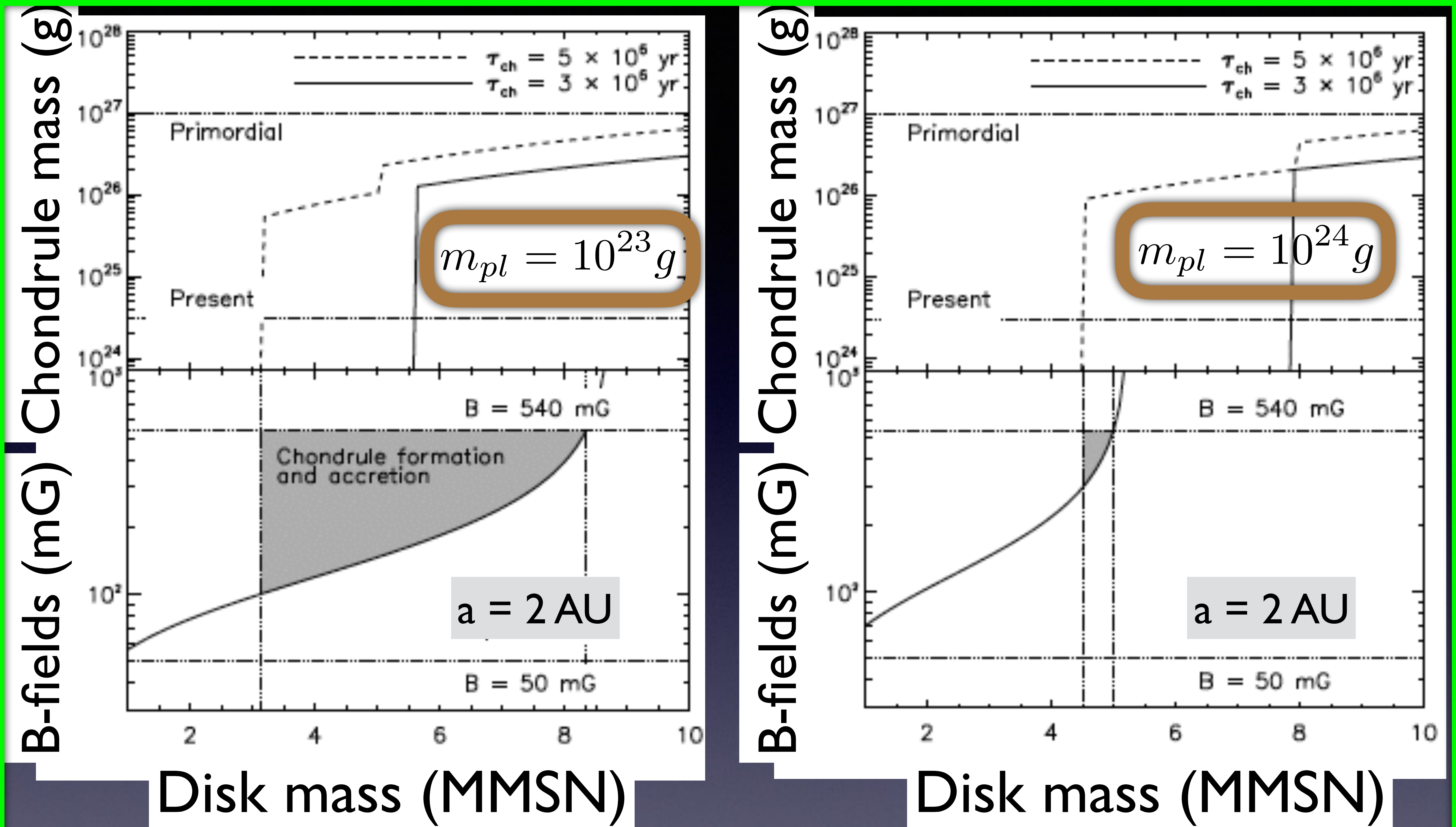
A large number of chondrules form in massive disks

A very strong magnetic field is needed for chondrules to have the same height as planetesimals

Planetesimals can reside in the chondrule sea, but no chondrules indeed

No chondrule formation due to a low disk mass

Hasegawa et al 2016b

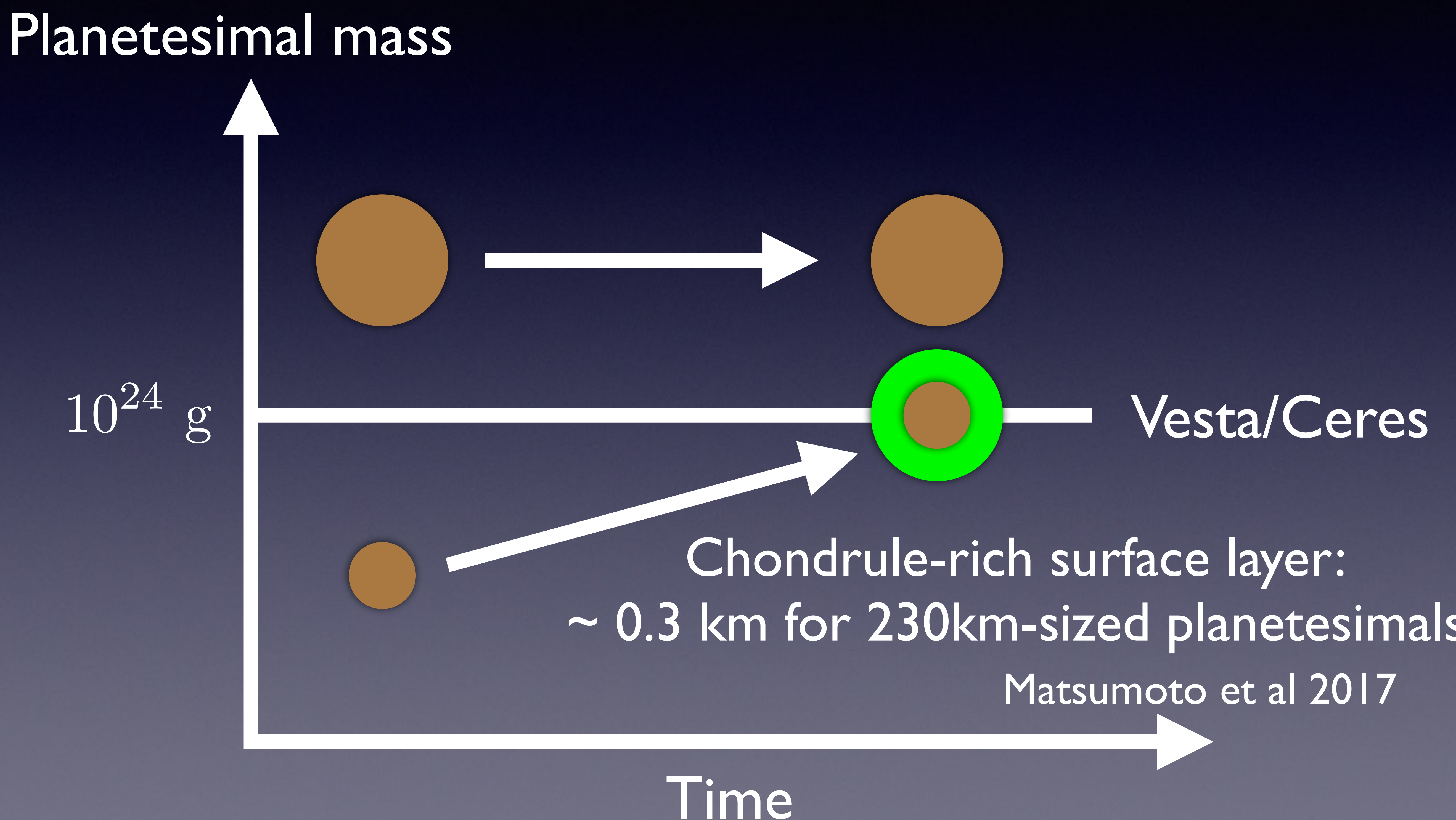


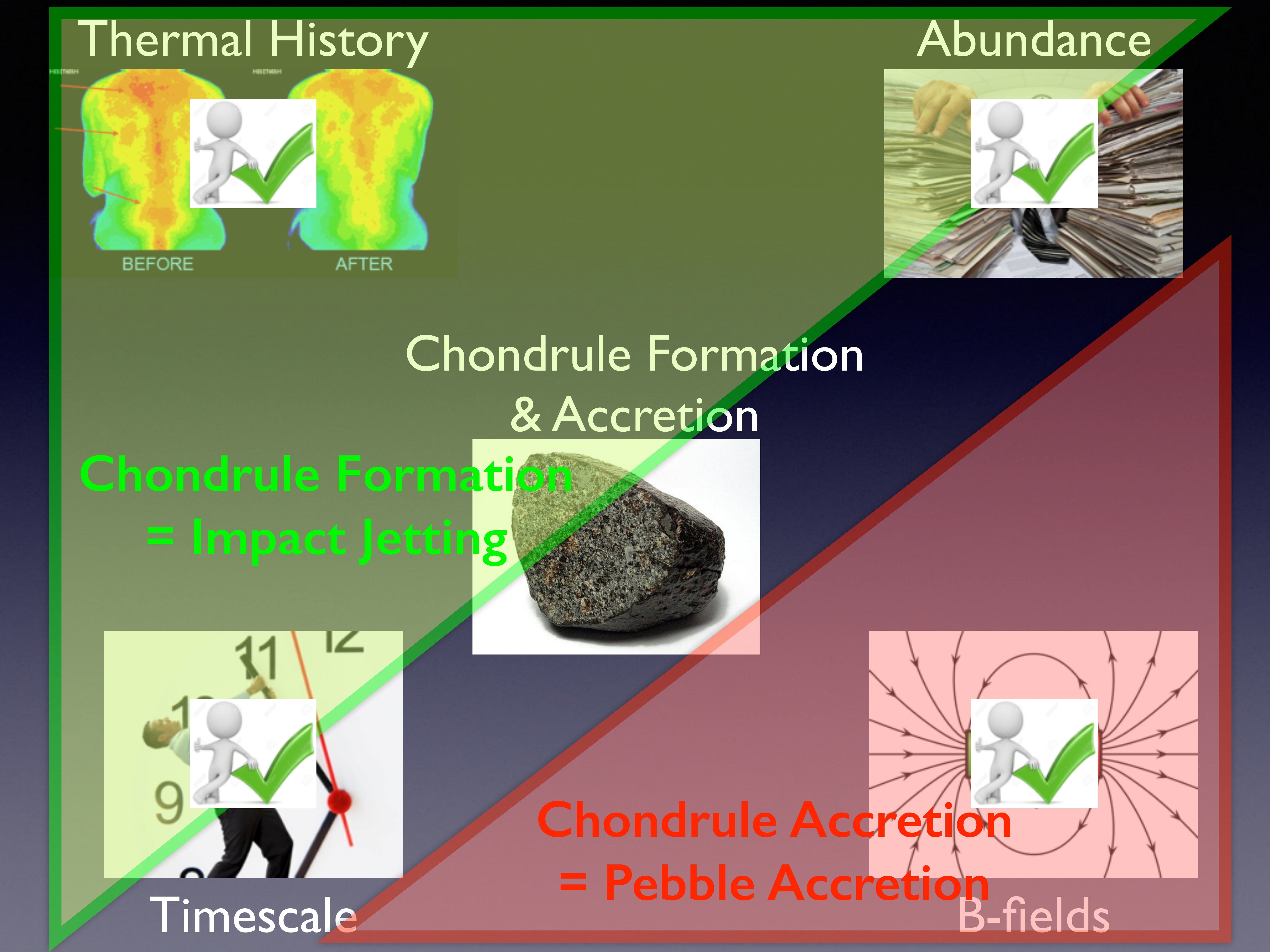
All the currently available meteorite data can be satisfied when the disk mass is < 5 MMSN the planetesimal mass is < 10^{24} g

Hasegawa et al 2016b

Our model needs a first generation of planetesimals that trigger impact jetting and serve as parent bodies to accrete chondrules

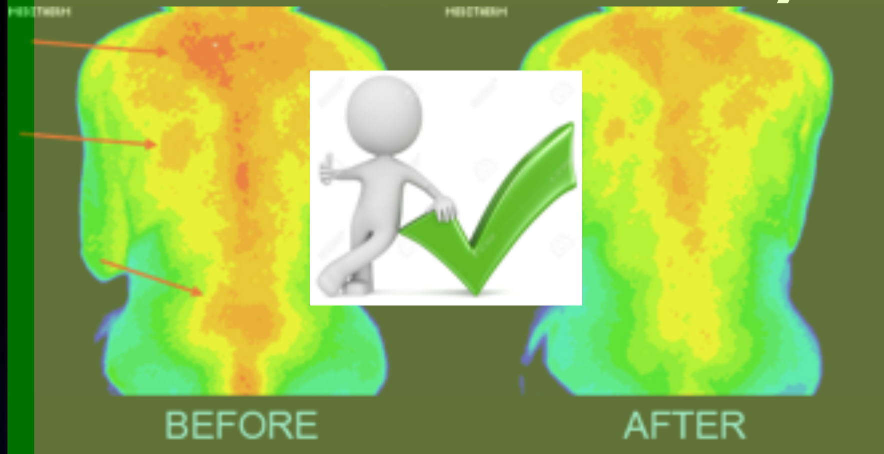
Hasegawa et al 2016b





Thermal History
BEFORE
AFTER
Abundance
Chondrule Formation
& Accretion
Chondrule Formation
= Impact Jetting
11
12
1
9
Timescale
Chondrule Accretion
= Pebble Accretion
B-fields

Thermal History



Abundance

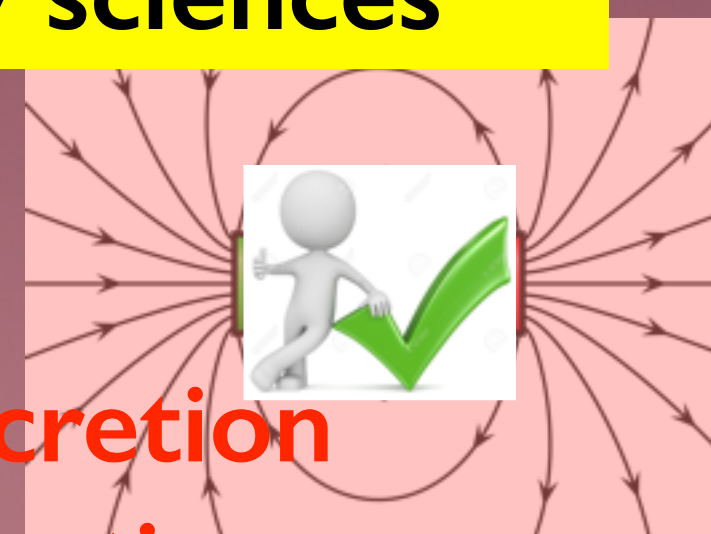
Cho

=

A great mixture of lab experiments, numerical simulations of collisions theory of planet formation, & disk physics

=

the heart of (exo)planetary sciences



Chondrule Accretion

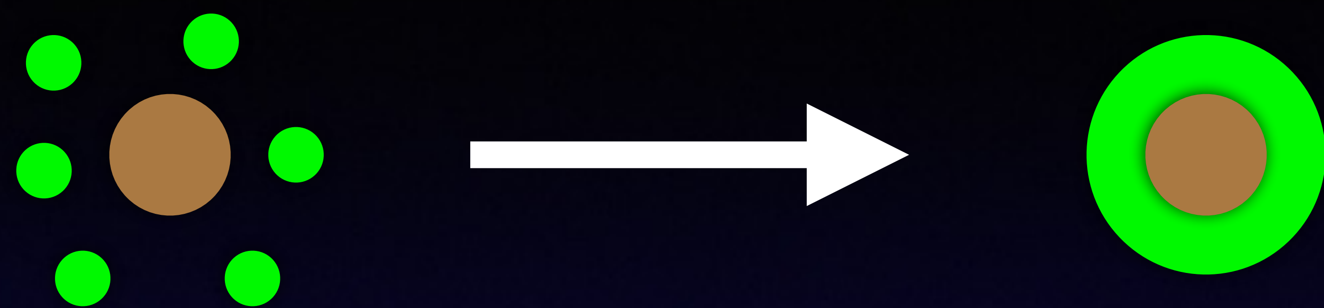
= Pebble Accretion

Timescale

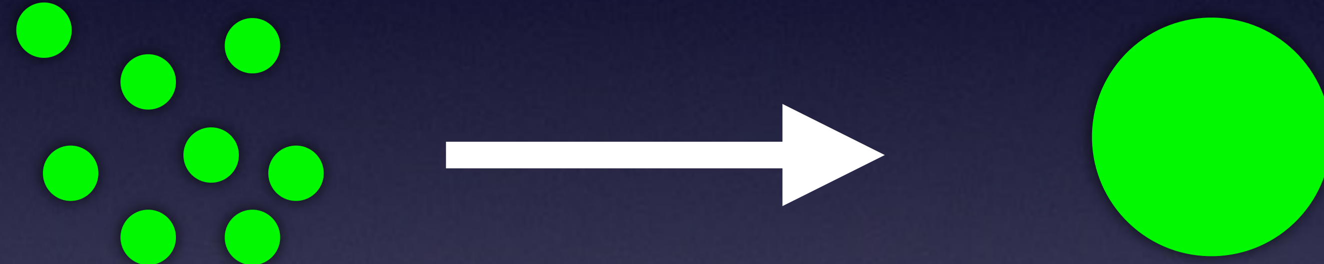
B-fields

Planetesimal Formation & Origins of Asteroids

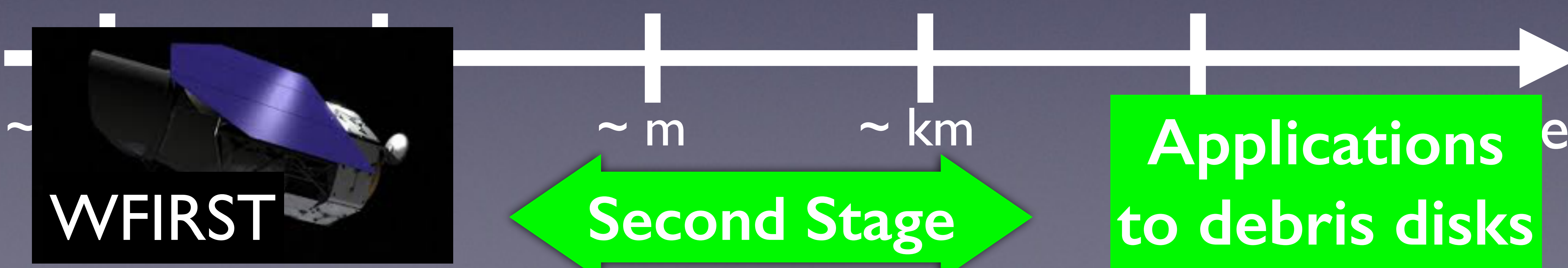
Scenario 1: Chondrule accretion

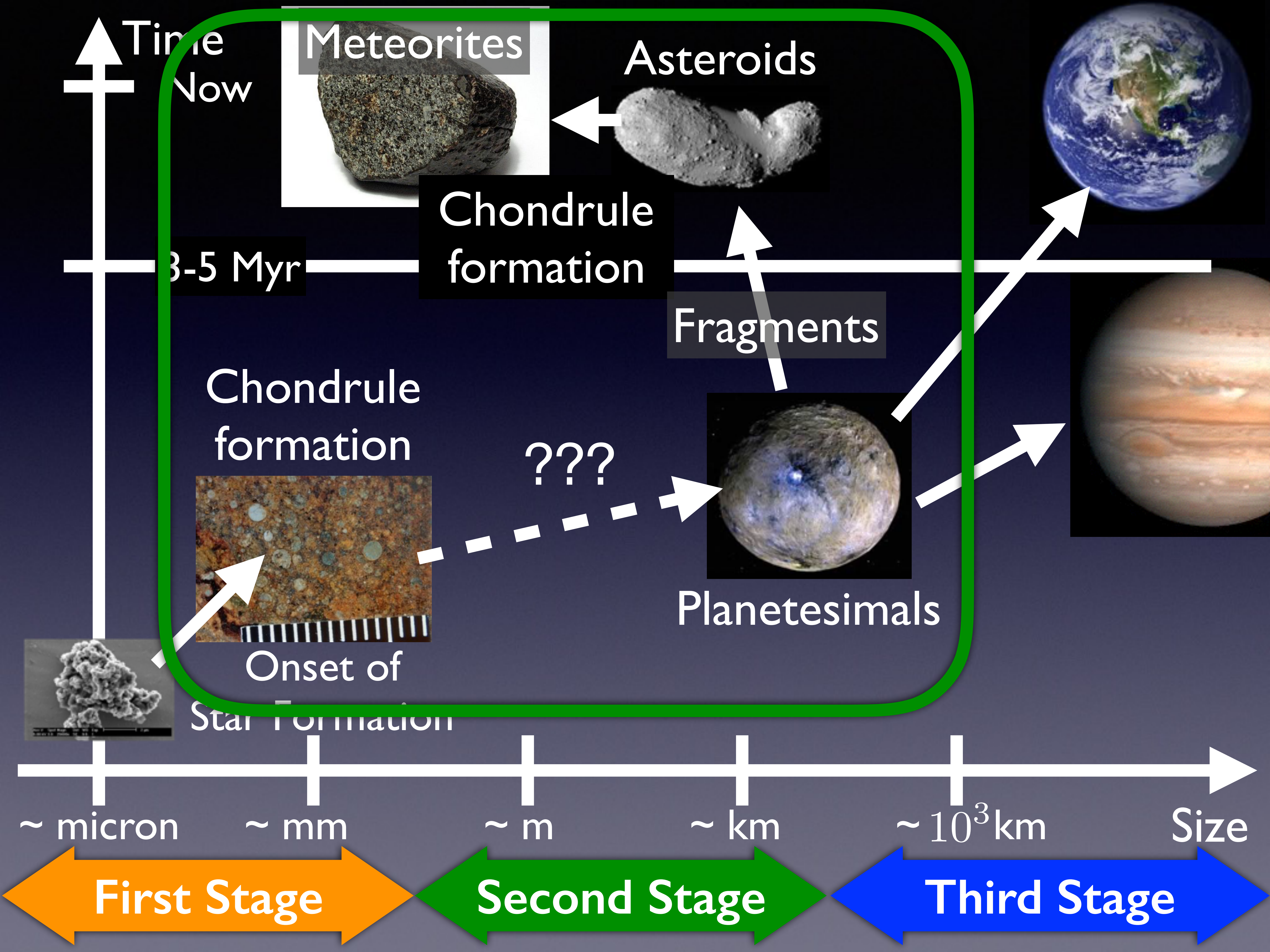


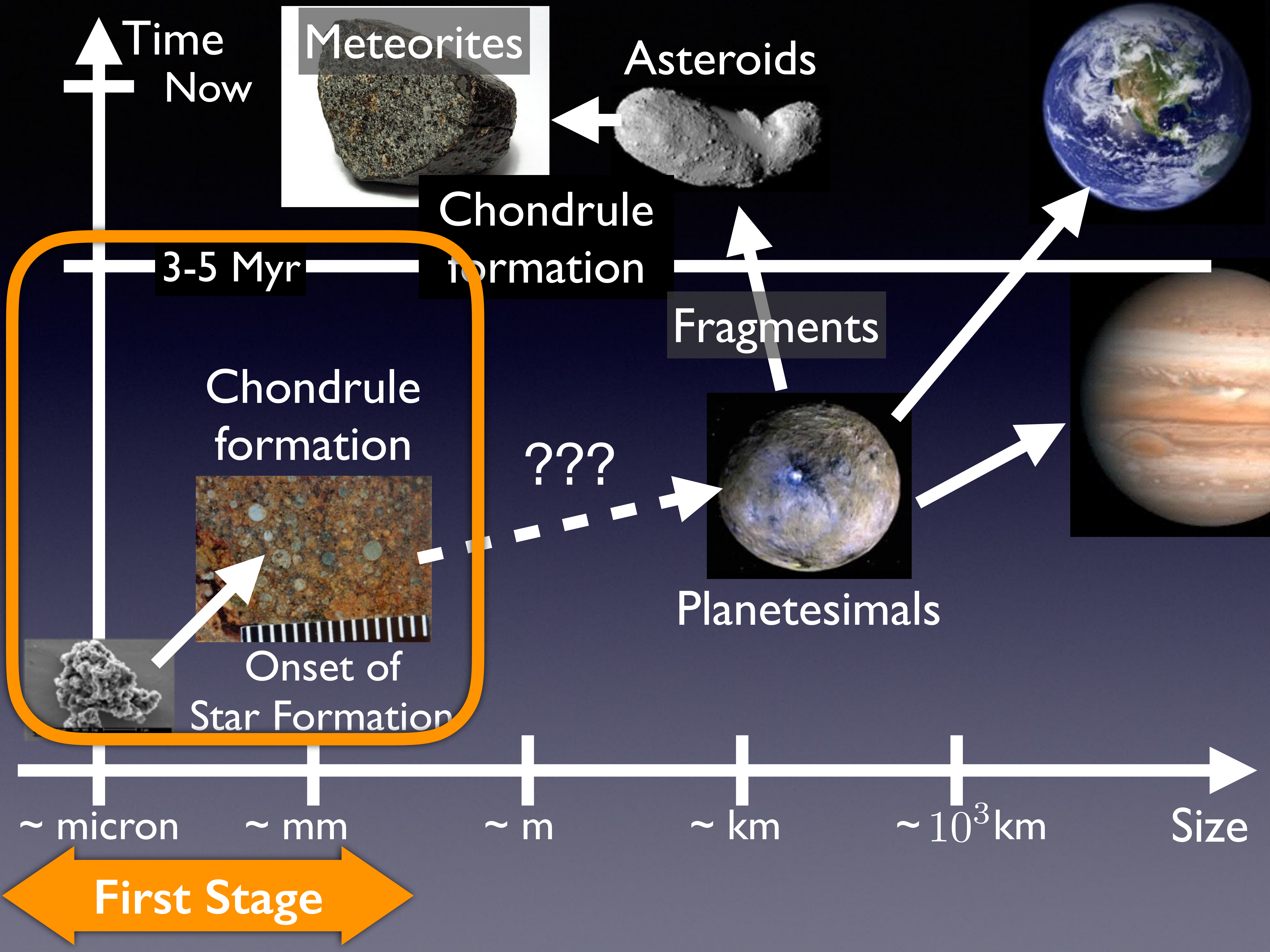
Scenario 2: Chondrule accumulation



We will **identify** formation mechanism(s) of planetesimals



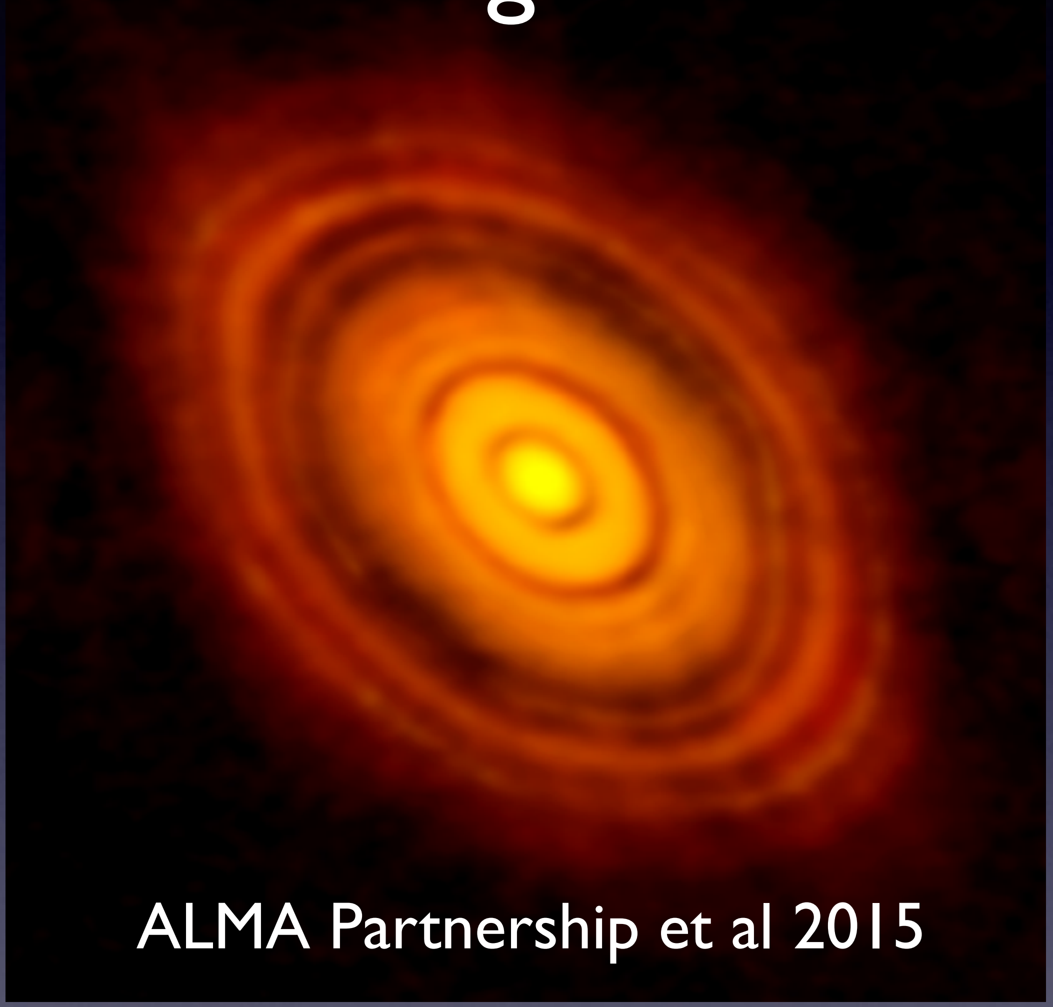

Time
Now
Meteorites
Asteroids
Chondrule formation
3-5 Myr
Fragments
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage



Time
Now
Meteorites
Asteroids
Chondrule formation
3-5 Myr
Fragments
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3km
Size
First Stage

Magnetically Induced Disk Winds and Transport in the HL Tau Disk

ALMA image of HL Tau



ALMA Partnership et al 2015

Key Observed Features

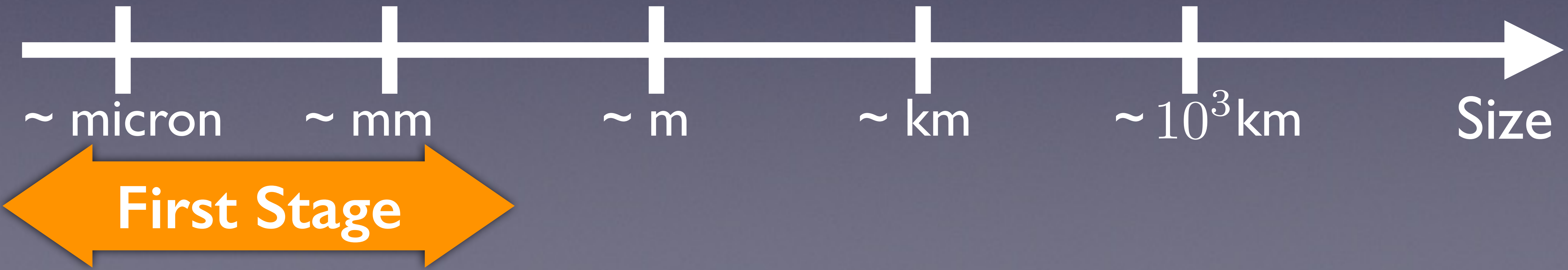
: a high disk accretion rate

: efficient dust settling Pinte et al 2016

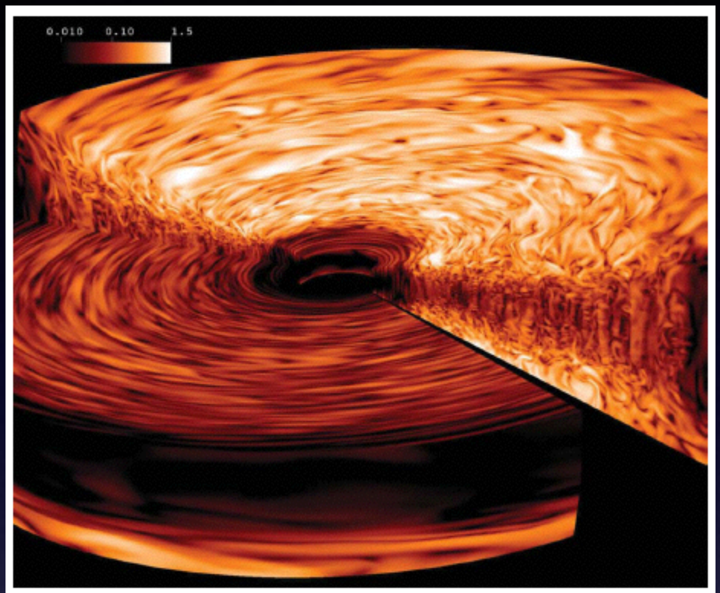
Our Disk Model

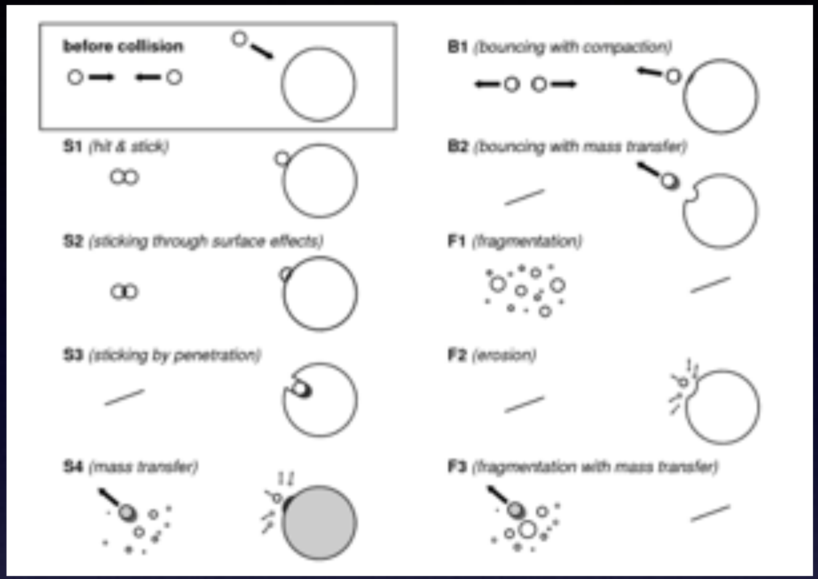
: magnetized turbulence and magnetically induced disk winds

Hasegawa et al 2017



Numerical Modeling of Dust Growth in Turbulent Disks





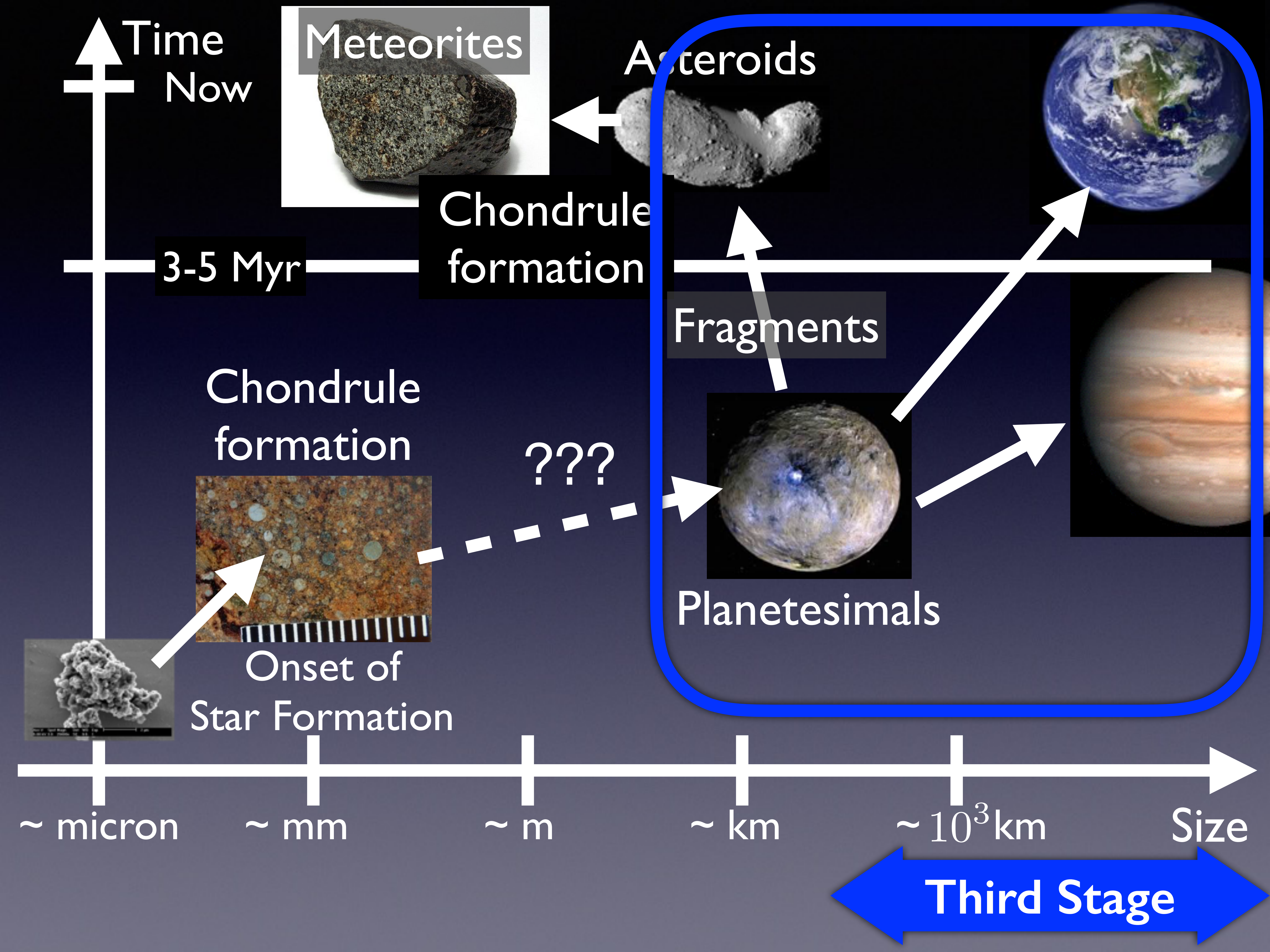
Flock et al 2011   Sengupta et al 2017 in prep

We will **specify** the distribution of planet-forming materials in disks

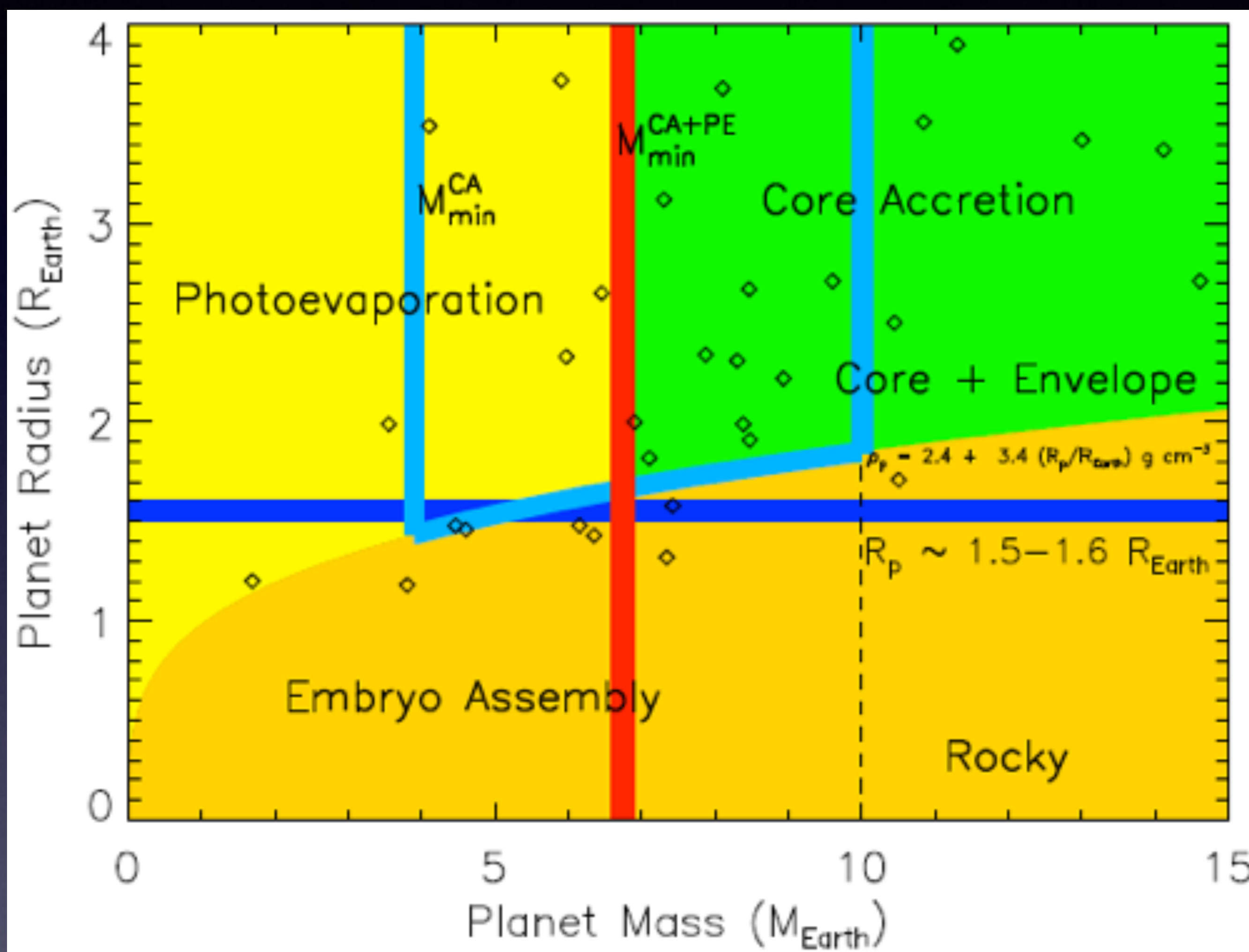
~ micron   ~ mm

First Stage

Applications to cloud/haze partciles in planetary atmospheres


Time
Now
Meteorites
Asteroids
Chondrule formation
3-5 Myr
Fragments
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
Third Stage

Link formation mechanisms of (exo)planets to their atmosphere



Close-in Super-Earths
: failed cores of gas giants

Population Synthesis
: a statistical understanding

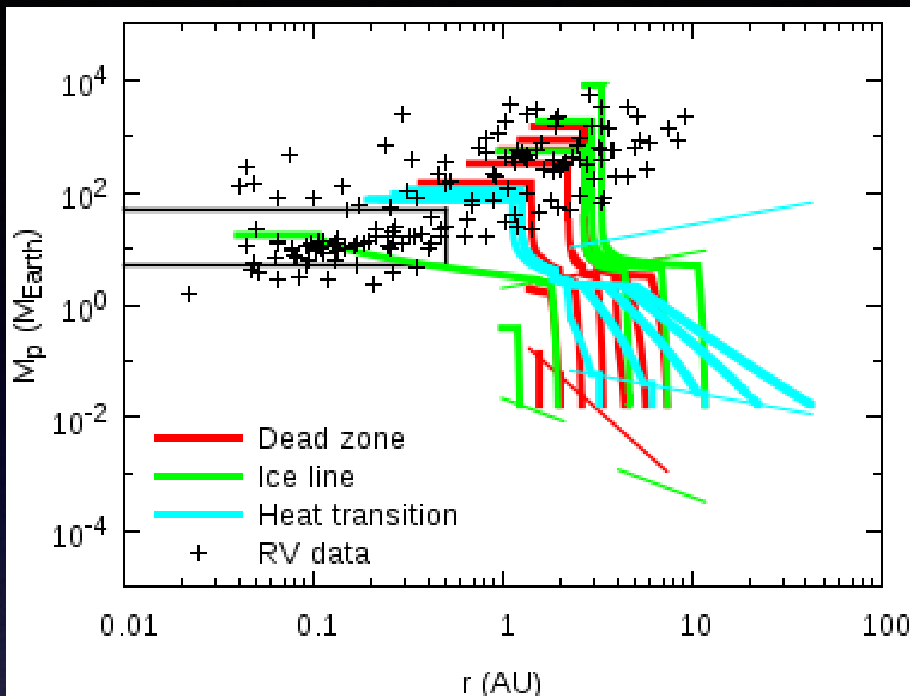
Mass-Radius Diagram
: useful for tracing down the formation history

Hasegawa 2016

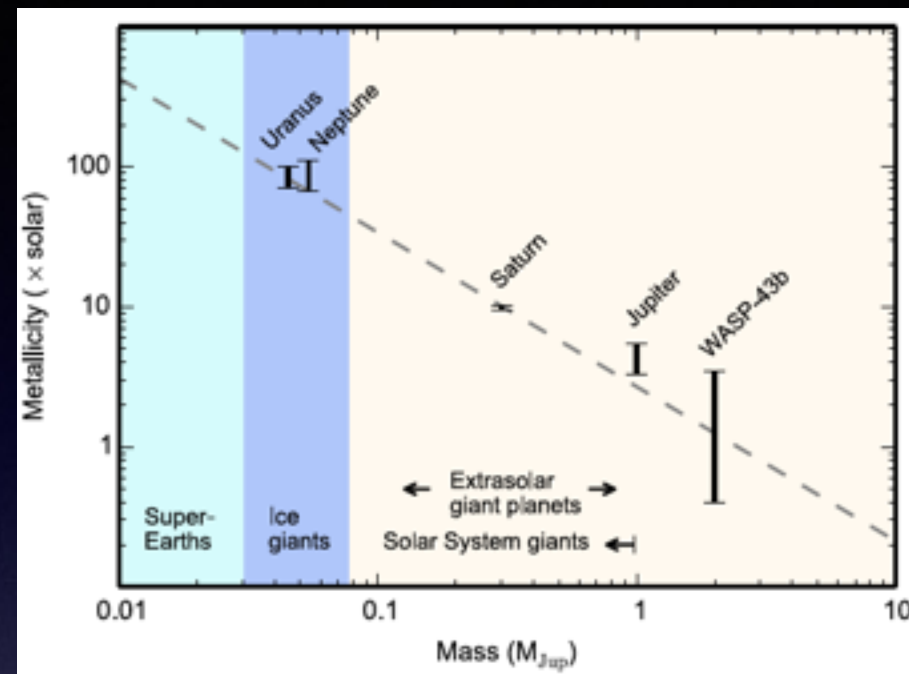
~ micron ~ mm ~ m ~ km ~ 10^3 km Size

Third Stage

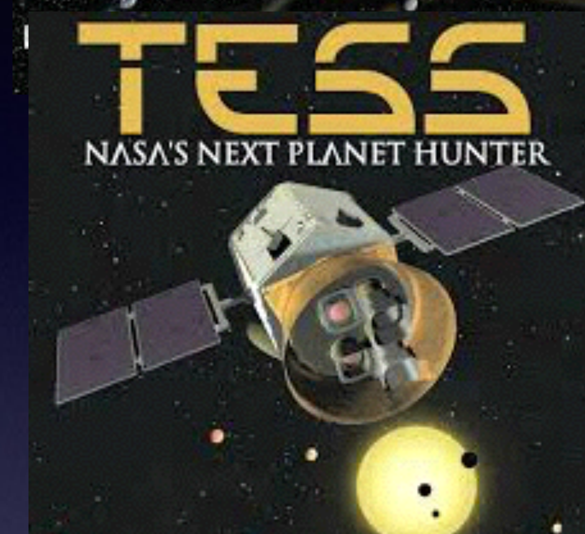
Gas Accretion onto Cores & Origins of Super-Earths



Hasegawa & Pudritz 2012



Kreidberg et al 2014



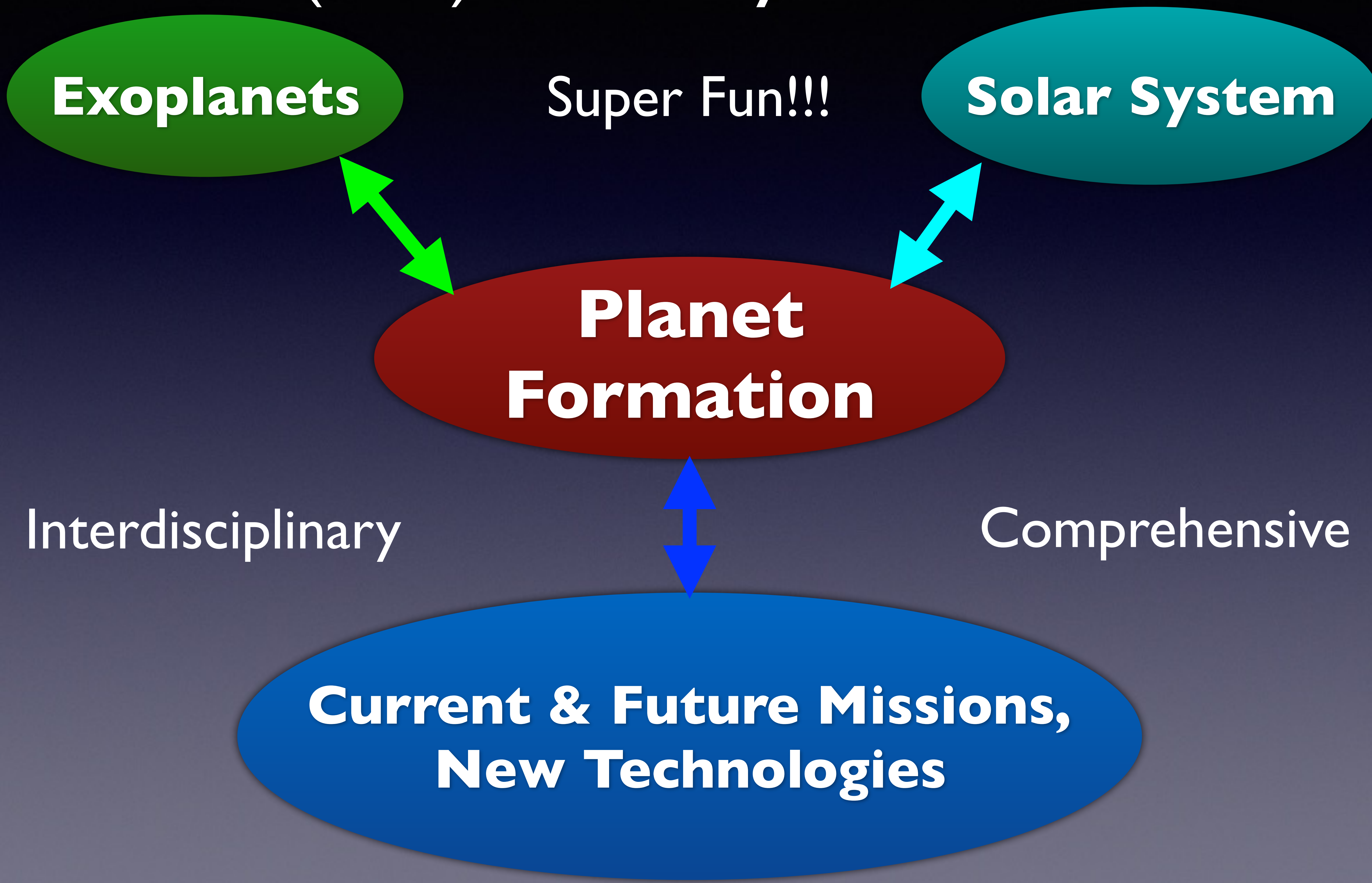
We will link formation mechanisms of (exo)planets to their atmosphere

~ … m ~ 10^3km Size

Applications to the Origin of the Solar System

Third Stage

Planet Formation is the Central in (exo)Planetary Sciences!!!



Summary

- Planet formation is the long journey from small dust grains to large planets
- A number of astonishing progresses allow a comprehensive examination of planet formation, covering the fill size range
- As an example, chondrule formation and accretion are discussed, focusing on the impact jetting scenario
- This scenario can account for a number of the currently available meteorite data, and may be useful for the sample return missions
- Further synergies between planetary and exoplanetary sciences will be undertaken to draw a better picture of planet formation and examine the origin of the solar and extrasolar planetary systems